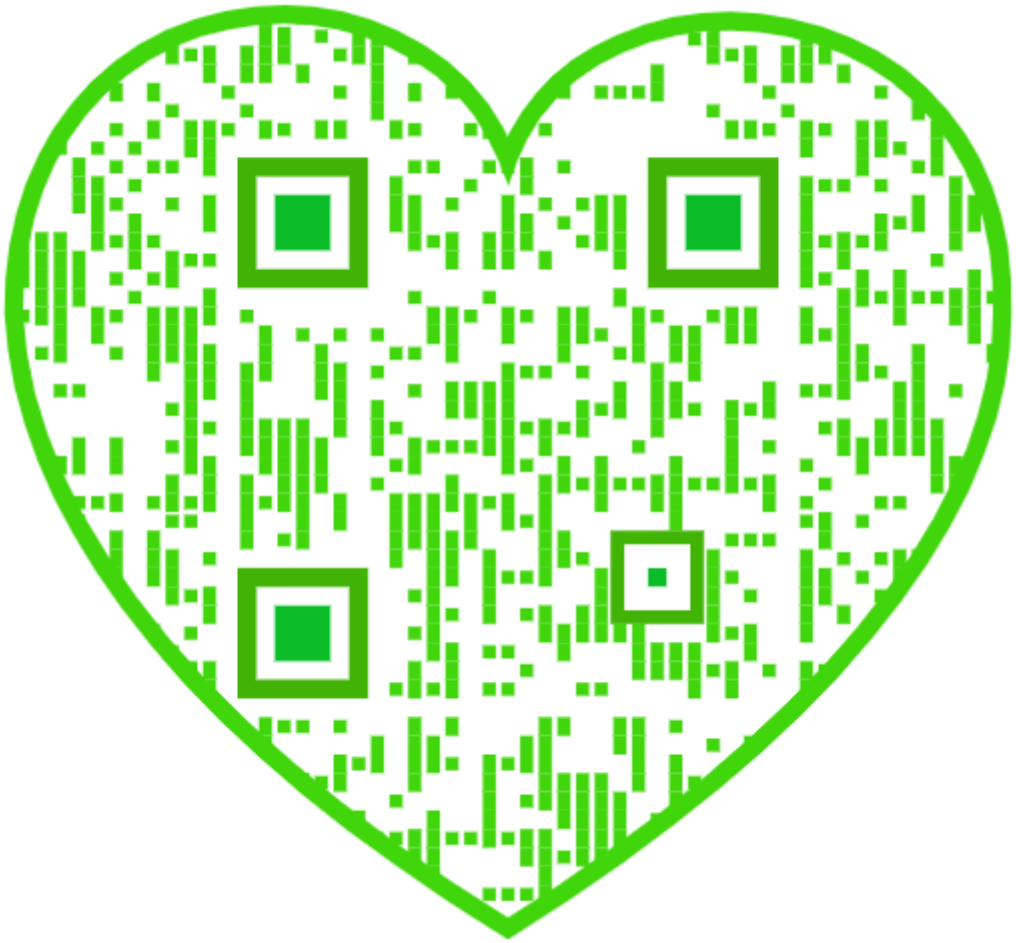

S. F. Emmons.

RE-DEPOSITS.

BY

SAMUEL FRANKLIN EMERSON

NEW YORK, N. Y.:
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1913.

Emmet.

ORE-DEPOSITS.

A Sequel to the Second Edition of "The Genesis of Ore-Deposits," by Franz Posepny and Others; Being a Compilation of Contributions to this Science from the Transactions of the American Institute of Mining Engineers, with a Critical Introduction and Synopsis.

BY

SAMUEL FRANKLIN EMMONS,

Economic Geologist of the U. S. Geological Survey.

Containing also a Biographical Notice of Mr. Emmons by Dr. George F. Becker; a Bibliography of the Subject by Prof. John D. Irving, H. D. Smith, and H. G. Ferguson; and a Preface by Dr. Rossiter W. Raymond, Secretary Emeritus of the Institute.

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CONTENTS.

PAGE

Preface, ... v
Introduction. By SAMUEL FRANKLIN EMMONS, ... vii
Biographical Notice of Samuel Franklin Emmons. By GEORGE F. BECKER, xxix

The Genesis of Certain Ore-Deposits. By S. F. EMMONS, ... 1
Structural Relations of Ore-Deposits. By S. F. EMMONS, ... 26
Geological Distribution of the Useful Metals in the United States. By S. F. EMMONS. Discussion, by JOHN A. CHURCH, ARTHUR WINSLOW, S. F. EMMONS, and WILLIAM HAMILTON MERRITT, ... 65
The Torsional Theory of Joints. By GEORGE F. BECKER. Discussion, by H. M. HOWE, R. W. RAYMOND, C. R. BOYD, and GEORGE F. BECKER, 92
The Allotropism of Gold. By HENRY LOUIS, ... 105
The Superficial Alteration of Ore-Deposits. By R. A. F. PENROSE, JR., . 110
Some Mines of Rosita and Silver Cliff, Colorado. By S. F. EMMONS, . 139
The Genesis of Certain Auriferous Lodes. By JOHN R. DON. Discussion, by JOSEPH LE CONTE, S. F. EMMONS, GEORGE F. BECKER, ARTHUR WINSLOW, W. P. BLAKE, and J. R. DON, ... 162
Influence of Country-Rock on Mineral Veins. By WALTER HARVEY WEED, 216
Igneous Rocks and Circulating Waters as Factors in Ore-Deposition. By J. F. KEMP, ... 235
A Consideration of Igneous Rocks and Their Segregation or Differentiation as Related to the Occurrence of Ores. By J. E. SPURR. Discussion, by ALEXANDER N. WINCHELL, ... 251
The Chemistry of Ore-Deposition. By WALTER P. JENNEY. Discussion, by JOHN A. CHURCH, ... 305
Ore-Deposits near Igneous Contacts. By WALTER HARVEY WEED. Discussion, by W. L. AUSTIN, ... 364
Ore-Deposition and Vein-Enrichment by Ascending Hot Waters By WALTER HARVEY WEED, ... 403
Basaltic Zones as Guides to Ore-Deposits in the Cripple Creek District, Colorado. By E. A. STEVENS, ... 411
The Geological Features of the Gold-Production of North America. By WALDEMAR LINDGREN. Discussion, by WILLET G. MILLER, and W. L. AUSTIN, ... 424
Osmosis as a Factor in Ore-Formation. By HALBERT POWERS GILLETTE, 450
The Ore-Deposits of Sudbury, Ontario. By CHARLES W. DICKSON, . . 455
The Genesis of the Copper-Deposits of Clifton-Morenci, Arizona. By WALDEMAR LINDGREN, ... 517
The Copper-Deposits at San Jose, Tamaulipas, Mexico. By J. F. KEMP, 557
The Magmatic Origin of Vein-Forming Waters in Southeastern Alaska. By ARTHUR C. SPENCER, ... 582
Genetic Relations of the Western Nevada Ores. By J. E. SPURR, . . 590
Are the Quartz-Veins of Silver Peak, Nevada, the Result of Magmatic Segregation? By JOHN B. HASTINGS, ... 621
The Occurrence of Stibnite at Steamboat Springs, Nevada. By WALDEMAR LINDGREN, ... 629

PAGE

A Summary of Lake Superior Geology with Special Reference to Recent Studies of the Iron-Bearing Series. By C. K. LEITH, ... 633

The Geological Relations of the Scandinavian Iron-Ores. By HJALMAR SJÖGREN, ... 657

The Formation and Enrichment of Ore-Bearing Veins. (With Supplementary Paper.) By GEORGE J. BANCROFT, ... 696

The Distribution of the Elements in Igneous Rocks. By HENRY S. WASHINGTON, ... 729

The Agency of Manganese in the Superficial Alteration and Secondary Enrichment of Gold-Deposits in the United States. By WILLIAM H. EMMONS, ... 759

Cognate Papers, ... 829

Bibliography of the Science of Ore-Deposits. By JOHN D. IRVING, H. D. SMITH, and H. G. FERGUSON, ... 837

Index, ... 929

ERRATUM.

Page 761, footnote [8]: for 1904, read 1894.

PREFACE.

At the Chicago meeting of the Institute in 1893, a remarkably suggestive and comprehensive paper on the Genesis of Ore-Deposits, by Prof. Franz Posepny, an Honorary Member of the Institute, was presented and discussed. This paper comprised the substance of the author's teaching on the subject at the Mining Academy of Pribram. It was translated by me from the German manuscript, and that translation, printed by the Institute, was the first publication in any language of this important treatise. I returned the original to Germany, where it was subsequently published.

Posepny's paper and its discussion, as contained in Vols. XXIII. and XXIV. of our *Transactions*, aroused wide-spread attention; and, in 1895, were reprinted in a separate volume. The first edition of this volume having become exhausted, a second and revised edition, comprising a large number of additional papers and discussions, was issued in 1902. As an indexed compilation of material scattered through our *Transactions*, the "second Posepny book" proved so convenient to instructors, students, and practicing experts that another, of similar character, is now called for.

The great recent progress of the science of ore-deposits has been largely due to the labors of the members of the U. S. Geological Survey and to their cordial co-operation in the work of the Institute, through contributions to its *Transactions*.

It was in this spirit of co-operation that S. F. Emmons, the distinguished economic geologist of that Survey, who had been since 1877 a member, and thrice during that period a Vice-President, of the Institute, consented to edit the present volume. This generous service I accepted with enthusiastic gratitude, both personal and official; for it relieved me from a task for which I could scarcely find the necessary surplus time and strength, and it secured the performance of that task by more competent hands and with far greater technical authority.

Mr. Emmons made the selection and arrangement of the

papers to be, in whole or in part, republished in the volume, and wrote the introductory and the supplementary chapter, thus finishing all the work which he had undertaken, except that final revision of the proof-sheets, which every author or editor claims as a right and needs in self-protection. But it was arranged between us that I should relieve him of the details of proof-reading, beyond his approval of the text of his own contributions; and this text had been so thoroughly discussed between us as to make any further change of it by him highly improbable. He had also approved the Preface which I proposed—and which, alas! is no longer appropriate.

The sudden death of Mr. Emmons has necessitated two changes in this book—the sorrowful preparation of a new Preface, and the introduction at the beginning of a Biographical Notice by Mr. George F. Becker, his life-long friend and colleague, commemorating the work of our lost leader and brother. In all other respects the volume is, as it would have been had he been spared to enjoy its completion and publication, the work of Mr. Emmons; and I cannot but feel that it will constitute a fitting memorial of him, wrought by his own hand. Only too often, death interrupts the sculptor at his work; but in this exceptional instance, the Messenger waited, and the message was no peremptory summons, but the gentler call, "Finish what thou art doing: then come—and rest!"

It should be added that, not wishing to alter the work of my friend, I have left the limit of selection where he left it; and therefore this "Emmons volume" contains no reference to Institute papers published later than the *Bulletin* of December, 1910.

Thanks are also due to Prof. John D. Irving, of the Sheffield Scientific School of Yale University, for the preparation, at Mr. Emmons's request, of the Bibliography which adds to the value of the book as a guide to further study.

ROSSITER W. RAYMOND,
Secretary Emeritus.

INTRODUCTION.

BY SAMUEL FRANKLIN EMMONS.

THE great demand for the "second Posepny book" on *The Genesis of Ore-Deposits*, published by the Institute in 1902, has abundantly demonstrated that such volumes fill a real want on the part of members of the Institute and others; and it has been judged advisable to prepare another, including additional important papers on this subject, which have been published in the *Transactions* of the Institute.

That this volume should not have an unwieldy bulk, it has been necessary to omit from it, either entirely or in part, papers which are more descriptive than genetic, and to select only those, the subject matter of which in great part contributes to the elucidation of general questions of genesis. A list of contributions that might have been included, except for this restriction, with a brief abstract of each, will be found at the end of the volume, in a supplementary chapter, followed by a general bibliography of the publications on the subject.

The arrangement of the papers is in general chronological; but such an arrangement is necessarily imperfect, because those in the previous volume were contributed in a middle period (1893 to 1901), and some of the papers now published were written before, but the greater part after, those dates.

The plan followed in the selection of contributions was to make them represent, as far as they can, the progress of investigation and thought on the subject of ore-genesis in the 40 years that have elapsed since the organization of the Institute in 1871. The papers themselves were not, however, written for any such purpose, but are merely a set of facts and deductions which the respective authors thought worthy, at the time they were written, of the consideration of their fellow-members; and since, as already stated, they were written in part before, but for the most part after, those in the previous volume, they do not present a consecutive or connected whole, but rather a disconnected series, which needs some kind of running commentary to bind them together. It is, therefore, the province of

this introductory chapter to indicate in a general way the progress of opinion in the period under consideration, and to show the place occupied and the part played in this progress by the different papers in this book and its predecessor.

At the time of the organization of the Institute in 1871—and indeed for many years after that time—so little was definitely known as to the processes entering into the formation of metalliferous deposits that purely geological criteria were rarely used in determining the value of an ore-deposit, or the best method of working it. In reading the reports of the mining engineers of those periods, one feels that such criteria were either entirely neglected or mentioned in a merely perfunctory way. The quantity and value of ore available or actually opened were determined; but for the estimation of its probable extent in unexplored ground, such estimates as were made at all were ordinarily based on an effort to prove the deposit to be a "true fissure-vein," in which it was then assumed that ore must extend to an indefinite depth, with possibilities of becoming richer. Among professional geologists there was no well-defined consensus of opinion with regard to the genesis of ore-deposits. It was the commencement of what I have elsewhere[1] called the period of verification, when the abundant and varied speculations and hypotheses of the pioneers in this department of study were about to be brought to the test of practical application in a wide field of newly-developed ore-deposits. Their minds were hence in the waiting or tentative stage.

Neither Whitney, who was the greatest American authority of his time, nor his European contemporary, Cotta, who, through Prime's translation of his well-known *Treatise on Ore-Deposits*, was for many years the recognized authority in American law-courts, had very decided opinions on the subject of ore-genesis. In their publications they presented with considerable impartiality the various views proposed by earlier students, leaving it to their readers to select that which might seem most worthy of belief.

It is difficult for the geologist of the present day to realize the condition of geological belief at that time, since a very

[1] Theories of Ore-Deposition Historically Considered, *Bulletin of the Geological Society of America*, vol. xv., p. 18 (1903).

great part of his fundamental data in geology is the result of much later investigations. It was the discovery, in the sixties, that the auriferous slates of California were of Jurassic age, which finally negatived Murchison's dictum that gold could be found only in Palæozoic rocks. It was not until well in the eighties that microscopical petrography had come to play any essential part in American geological investigations. Before that, it was only personal observation underground, supplemented occasionally by a few laboratory or blow-pipe tests, that furnished information as to the processes going on in the earth during ore-deposition; and, as all ores were thought to be necessarily the filling of pre-existing open spaces, evidence of replacement was seldom looked for.

Richthofen's report on the Comstock lode, in 1865, may probably be regarded, in view of his previous career, as representing the most advanced and best-founded views of his time. After professional study of the metallic deposits of Hungary, the geological relations of which most nearly approach those of our Cordilleran system, he had accompanied, as geologist, the scientific expedition of the Austrian government in its voyage around the world, and had remained in California to take part in Whitney's survey of the Sierra Nevada. His *Natural Classification of Eruptive Rocks* had been a great step in the scientific study of igneous action, and was generally accepted by petrologists, until it was finally superseded, some 20 years later, through new light thrown upon the subject by the modern science of microscopic petrography. Richthofen regarded the Comstock lode as a true fissure-vein—that is, as a result of dynamic action, cutting through different varieties of rock, and extending to indefinite depth. Its mineral contents he believed to have been deposited from solution, the silica having been precipitated in a first stage, and the metallic minerals introduced in a second stage, after the fissure had been re-opened. The extensive decomposition of the adjoining country-rock could not, in his opinion, be explained by thermal action alone; and he therefore assumed that a process had taken place, similar to that observed in the solfataras of active volcanoes, which he therefore called "solfataric action." As the source of the water which, acting as a solvent, had brought in the chlorine, fluorine, and other vein-materials, he

found the ocean too far away, and therefore resorted to the waters of the Great Basin, which have a composition similar to that of the ocean. These he assumed to have descended to the heated region, where their chlorine and fluorine had become as active as they are supposed to be in actual solfataras. For the source of the mineral substances he says: "We have to look to the action of these elements on the surrounding rocks," which is an application of the lateral-secretion theory. It is noteworthy that, in spite of his characterization of the action as solfataric, he considers the waters to have been of meteoric origin. This was the most definite scientific opinion that could be given at that time by the leading economic geologist of the day. What the average mining engineer would say is illustrated by the statement of A. Sutro in the same report, which was evidently a paraphrase of Richthofen's opinion, put in terms more comprehensible to the average layman. Sutro says: "The Comstock lode is a true fissure-vein . . . . through which open fissure ascended steam and vapors, gases, acids, sulphur, chlorine, and fluorine, carrying with them silica and metallic particles in a volatile form, which in course of untold ages gradually filled up the fissure, and, after undergoing many chemical changes, formed what is now known as the Comstock lode."

In the later, more detailed and exact, study of the Comstock by King and Hague, published in 1870, the former declines to go into abstruse speculation as to the genesis of the metals, it being his opinion that, in the existing state of knowledge with regard to ore-deposits, such speculations were more or less futile, inasmuch as they could not be supported by facts. It was in pursuance of this idea that, on assuming the Directorship of the newly established U. S. Geological Survey in 1880, Mr. King founded the Division of Mining Geology, to which about half of the entire appropriation granted by Congress was allotted. To Mr. Becker and myself, whom he placed in charge of this division, he pointed out, in the following terms, the ultimate results at which he aimed:

"You will make accurate, detailed, and exhaustive studies of the Comstock, Eureka, and Leadville districts; and, when these are completed, your principal assistants will be competent to undertake similar studies of other important mining-districts for which the necessary money will be furnished, thus successively dupli-

cating the field of work, so that at the expiration of, say, ten years, the varied types of deposits in all important mining-districts will have been studied; and the many phenomena bearing upon the genesis of ore-deposits thus accurately determined should be sufficient for a new theory of ore-deposits, based upon facts accurately determined in the light of modern geology rather than, as is that of the present day, upon theoretical speculations."

While the course of events has not been exactly that which Mr. King planned, and results have been slower in coming, and less definite and decisive, than his sanguine temperament anticipated, they have been, nevertheless, such as to demonstrate the wisdom of his plan. An important factor has been the hearty concurrence and aid in this work afforded by individuals among the body of mining engineers, as soon as the first results of the work planned by Mr. King had demonstrated the immediate and practical aid to mining which might be afforded by a knowledge of the geological relations of an ore-body. It is this factor, emphasized by Dr. Raymond in his Preface, which is especially brought out in the present volume.

The monographic reports of mining-districts by the U. S. Geological Survey presented all the facts discernible with regard to the geological relations of the deposits in each district, with the conclusions that might be drawn for that special district; but it was many years before a sufficient number of districts had been studied to permit any generalization applicable to all deposits. These were naturally first formulated by the geologists actually occupied in that work, and were mainly published in the *Transactions* of this Institute, because they would thus reach a wide audience of working mining engineers, and lead them to contribute facts and discuss results. Thus, the first two papers in this volume present conclusions drawn by me from the early years of my work on mining-geology, mainly in Colorado.

No. 1. *The Genesis of Certain Ore-Deposits.* By S. F. Emmons. This paper was written to correct certain misapprehensions by critics of my views as given in the Leadville report. The theoretical conclusions therein expressed were of a preliminary rather than final nature. The more important of these conclusions were:

a. As to the manner of deposition: that ore-deposition by replacement or metasomatism is not confined to easily-soluble

rocks like limestone, but is quite common in vein-deposits, even in siliceous crystalline rocks.

b. As to genesis: that most ore-deposits are genetically connected with eruptive or igneous rocks; and,

c. As to the source of the metals: that for ore-deposition from percolating waters (assuming, as was then universal among geologists, that practically all waters circulating within the earth's crust are of meteoric origin), it is more reasonable to suppose that these waters derive their metallic contents from bodies of igneous rocks at moderate distances from the deposits than from the unknown depth or barysphere. The main reason for this assumption is, that the hypothetical barysphere (or region where the rocks are distinctly heavier, hence richer in heavy metals, than those that come under observation) must be at such great depths within the crust that it would have been beyond the reach of meteoric water. Furthermore, the suggestions of Bischof and Sandberger had pointed out a means of verification of this theory, of which the derivation from unknown depths is not susceptible. A modification of the lateral-secretion theory much broader than the restricted one put forth by Sandberger was therefore adopted as affording the most fruitful field for further investigation and verification.

No. 2. *On the Structural Relations of Ore-Deposits.* By S. F. Emmons. This presents my generalizations on the geological character of the channels through which ore-bearing solutions may have reached the loci of various ore-deposits, the conclusions being that such channels have mostly been produced by dynamic action and are in the nature of actual rock-fractures or fault-fissures, even where no displacement is discernible.

No. 3. *The Geological Distribution of the Useful Metals in the United States.* By S. F. Emmons. As here presented, this is a series of extracts from a paper presented by me at the Chicago meeting of the Institute (1893), containing the views then entertained as to the genesis of the respective metals. These views were still tentative, and their presentation was very much in the nature of a report of progress; since the special studies of mining-districts made by the U. S. Geological Survey had not proceeded with the rapidity originally contemplated, and the material for a new theory of vein-formation was still far from complete.

No. 4. *The Torsional Theory of Joints.* By George F. Becker. This is a scientific demonstration, from the point of view of terrestrial physics, of the laws governing rock-fractures, which he groups under the term of "joints," giving the criteria by which the effects of the agencies of pressure, tension, or torsion may be recognized. While the term "joints" is applied by him to those partings in rocks on which the throw is not apparent without close observation, the laws governing them are applicable to the larger fractures on which mineral veins have formed.

Meanwhile, an important contribution to genetic investigation had been made by the Norwegian geologist, Vogt, in demonstrating by microscopical study that certain titaniferous iron-deposits of Sweden were in the nature of concentrations taking place before consolidation in the fused magma of an eruptive rock, on the principle of magmatic differentiation recently announced by leading petrographers to account for the varying composition of eruptive rocks in a given region. Such magmatic concentration, I maintained, would furnish a means of accounting for the localization of great mineral deposits in limited areas or mining-districts, and their absence in other areas where eruptive rocks are equally abundant, by the assumption that, in the fused magmas from which the eruptive rocks of the mining-districts had been formed, there had been a concentration of metallic minerals previous to consolidation. In so far, then, a fact of observation had been contributed to the hypothesis that the metals of ore-deposits might more probably have been derived from bodies of igneous rocks which had consolidated near enough to the surface to be within the reach of meteoric waters, rather than directly from the unknown depths of the barysphere.

Posepny's well-known paper on *The Genesis of Ore-Deposits*, read at the Chicago meeting, and forming the leading article in the first and second "Posepny volumes," published by the Institute, stated the strongest argument yet presented in favor of the ascension theory, as distinguished from Sandberger's narrow conception of the lateral-secretion theory; and had a great influence in bringing about a revolution in the mind of the professional public against lateral secretion in general. In his advocacy of the direct derivation of the metals from the bary-

No. 7. *Some Mines of Rosita and Silver Cliff, Colorado.* By S. F. Emmons. This paper gives the record of actual observation of the occurrence of vadose and deep-seated waters in one and the same mine (the Geyser), separated by a zone, over 500 ft. thick, of perfectly dry rock, where observation, as well as analysis, gave an entirely independent source for each of the respective kinds of water. While the conclusions drawn in this paper are based on the then-prevailing belief that all the waters circulating within the earth's crust are primarily of meteoric origin, the facts recorded have an equally important bearing upon the recently-adopted theory of the magmatic origin of most deep-seated waters.

No. 8. *The Genesis of Certain Auriferous Lodes.* By John R. Don. This is an abstract from a record of exhaustive chemical research, carried on for seven years by Dr. John R. Don, of New Zealand, into the possible source of gold, which has contributed most important chemical data to the general subject of genesis. Dr. Don's analyses confirm the statements of previous investigators as to the presence of gold in extremely dilute solution in the waters of the ocean; and his experiments render it highly improbable that gold can have been precipitated so as to form a part of sedimentary rocks; thus confirming the assumption that its source is to be looked for in igneous material. In igneous rocks, however, he determines that it is not contained in the bisilicates, but is necessarily associated with pyrite; and, as he assumes that the pyrite is a later introduction since the consolidation of the rock, he concludes that the gold could not have been derived from the rocks examined by him, but must have been precipitated from solutions ascending from rocks deeper than any now exposed at the surface, without, however, concerning himself "with the question whether this source is the vague barysphere with its somewhat apocryphal contents of heavy metals." As will be seen from the discussions[2] of this paper, Dr. Don's critics, while not questioning the accuracy of his determinations, do not agree on all points with the conclusions that he saw fit to draw from them, and do not admit that the impossibility of derivation from igneous rocks is conclusively proved.

[2] This volume, pp. 202 to 215.

Chronologically, the next steps in the development of the theories of genesis were taken at the Institute meetings of 1900 and 1901, at Washington and Richmond, respectively. The papers presented at these meetings were of the greatest and most critical importance in the development of the various stages of the history of ore-genesis, and have been included in the already-published volume, together with the treatise of Posepny, which they so seriously modify and in some respects even negative. Space will not permit a characterization of them at all commensurate with their importance; and they will only be referred to briefly, in such a way as to give each of them what appears to be its proper place in the historical development of opinion.

In his *Principles Controlling Ore-Deposition*, Van Hise presented a philosophical treatment of the entire question of underground circulation as applied to ore-deposits, based on experimental data with regard to underground circulation furnished by the Water Supply Department of the U. S. Geological Survey. In this he explained, more definitely and in greater detail than had hitherto been done, the manner in which surface-waters, in their downward course, spread over wide areas within the crust, and, as they turn upward, unite in the larger trunk-channels through which they ascend to reach the surface again at some outlet or point of run-off. The element of lateral movement in underground circulation was shown to be, therefore, much larger than had previously been conceived. Van Hise believed that the descending and laterally-moving waters had been the main agents in taking up metallic minerals from the rocks through which they passed, and that from these waters, ascending through trunk-channels, the greater part of ore-deposition had taken place. He believed in a ground-water level, but held that downward-moving and oxidizing waters might penetrate some distance below this level, and that when such mineral-charged solutions met other similarly-charged solutions, ascending along trunk-channels, extraordinarily rich deposits would be formed; whereas below, in the trunk-channels, the ores would be mainly low-grade pyritous ores.

The following paper in the second Posepny volume contains my announcement of the important doctrine of "Sulphide

Secondary Enrichment," which I had really discovered through my studies, in 1896, of the veins of Butte, Mont., although I had withheld its formal announcement, that I might test the general applicability of the theory by the study of other deposits, especially those of copper, in which the results are more easily observable than in those of other metals; and, further, in order to investigate the chemistry of the processes involved; for, according to the generally-accepted theory of a universal underground water-level, descending oxidized solutions would become diluted and neutralized on reaching this underground sea, so as to lose their distinctive characters. As explained in this paper, I do not believe in any such universal level, but hold that the level to which water will rise in a given mine or district is dependent on the structural relations in that particular mine or district, which thus constitutes a separate and independent hydrostatic basin, so that the water-level, at points no great distance apart, may be respectively much higher or lower.

The next paper in the second Posepny book, by W. H. Weed, on *The Enrichment of Gold and Silver Veins*, is of similar import. In the original survey of the Butte district, in 1896, Mr. Weed had acted as petrologist in charge of surface-geology. Having listened to my discussion of the importance of this new doctrine of enrichment by descending waters below the ground-water level, Mr. Weed had appreciated its significance, and, unknown to me, had studied its working in gold- and silver-mines, principally in Montana—of which study this paper was the result. He announced, for the winter meeting of the Geological Society of America, an article on this general subject, which was not, however, actually read at the meeting of the Geological Society in December, 1899, but was written for that meeting at the same time that I was preparing, for the Institute meeting of February, 1900, my paper on *The Secondary Enrichment of Ore-Deposits.*

In the second Posepny volume, these contributions on secondary enrichment are followed by a very important paper of Waldemar Lindgren, read at the same meeting, and entitled *Metasomatic Processes in Fissure-Veins.* This is a most exact and philosophic discussion of the part which metasomasis has played during ore-deposition in various classes of deposits, and

the changes thereby brought about in the wall-rocks, as well as in the veins themselves. Mr. Lindgren shows this process to have an even wider field of application in ore-deposition than had been assumed by me in the early eighties, although at that time my assumption was regarded as extra-hazardous; but he deprecates the exaggerated importance assigned to it by some over-zealous supporters of the metasomatic theory.

Able discussions of all these papers by prominent economic geologists, European as well as American, were read at the succeeding meeting of the Institute in February, 1901, at Richmond, Va., and are incorporated in the latter part of the second Posepny volume, together with two papers, which pursued a new line of reasoning, destined to have a most important influence on the whole question of genesis, and to set it, so to speak, on a new basis. These were the paper of Prof. J. F. Kemp, on *The Rôle of the Igneous Rocks in the Formation of Veins*, and that of Waldemar Lindgren, on *The Character and Genesis of Certain Contact-Deposits*. Both authors protest against what they regard as the too great importance assigned by Van Hise and others to the agency of meteoric waters in vein-formation—Kemp attacking the question on theoretical grounds, and Lindgren bringing practical proofs from a large and increasingly-important class of deposits that could not have been formed by meteoric waters.

Kemp enters at once into the broad question of the adequacy of meteoric waters to do what had been claimed for them, in bringing vein-material up from the barysphere, and makes a strong argument against this adequacy and in favor of the probability that not only the vein-materials themselves, but the waters that carried them, were derived from igneous rocks. A significant indication of the inadequacy of meteoric waters was furnished by the recently-observed fact that the rocks at the bottom of very deep mines (1,000 m.) are nearly or absolutely dry. The evidence that water in quantity could have been furnished by igneous magmas is necessarily indirect, but was strengthened, a short time after the publication of these papers, by the conclusions reached by Suess, from the prolonged studies that had been made of well-known European thermals, namely, that the waters of many thermal springs are entirely derived from cooling igneous magmas, squeezed

out, as it were, during the process of crystallization. Such waters having never before appeared at the surface, Suess calls them "juvenile" waters; but in America they are perhaps more frequently called *magmatic* waters. Suess admits, however, that the waters of some springs are entirely of meteoric origin, and that others probably have a mixed meteoric-magmatic origin, while a portion only are exclusively magmatic.

Lindgren's paper on contact-metamorphism was also a protest against the extreme views of Van Hise and others, through its demonstration that deposits of this class must have been formed by direct emanations from cooling igneous magmas at a temperature above the critical point of water, and hence in gaseous or pneumatolytic state. He expressed the belief (which he confirmed later by actual observation in nature) that, contrary to the statement of European petrographers, this metamorphism involves also an actual transfer of material from the intruding magma to the invaded rock. When he wrote this paper, there were, it is true, few deposits of economic importance to which a contact-metamorphic origin could, with certainty, be ascribed; but since then, as their characteristics have become better known, the number of such deposits discovered has been so greatly increased that they constitute in reality the strongest argument in favor of the theory of the magmatic origin of vein-forming waters.

After the appearance of these two papers, there was a marked revival of discussion on the ultimate source of the metals—the question, as it came to be called, of "meteoric versus magmatic waters." The advocates of the latter origin often went further than either Kemp or Lindgren would have been willing to go, in assuming it as proved that the great majority of ore-deposits have been deposited from highly-heated waters of magmatic origin—that is, waters occluded in igneous magmas, and expelled or squeezed out of them during the process of crystallization. This theory has the great merit of furnishing a ready explanation for many facts connected with ore-deposition for which it has hitherto been difficult to account. If, for instance, it be admitted that the mineral-bearing waters are furnished by the cooling magmas, it is no longer necessary to assume that surface-waters circulate to impossible depths; since

the magmas themselves, which have unlimited powers of penetration, may have risen to within the region of possible circulation before the commencement of the process of consolidation which would have squeezed out the mineral-bearing waters. Some conservative minds still require more definite proof that magmas contain water in sufficient quantity to fulfill the requirements of this hypothesis; for, while petrographers in general admit the possibility that during the consolidation of magmas mineral salts may have been pneumatolytically forced into the adjoining rocks, many of them doubt that such consolidating magmas are of themselves capable of furnishing the long-continued supply of water, carried through long distances, which seems to be required for the formation of certain classes of deposits. Direct proof of what has taken place at such great depths cannot, it is evident, be obtained. It is, therefore, all the more important to find well-determined facts of observation or experiment that may indirectly contribute to this end. In the later portion of the present volume will be found many papers, the bearing of which upon questions of genesis may seem rather remote, but which have been selected because they contain scientific data which may be found later to have inductive value in testing some of the current theories.

Returning from this discussion of previous contributions, required for the continuous history of the literature of the subject, as embodied in our *Transactions*, I resume the consideration of the papers contained in the present volume.

No. 9. *The Influence of Country-Rock on Mineral Veins.* By W. H. Weed. This is a compilation of facts bearing on the change of the mineral contents of vein-deposits as such deposits pass from one rock into another.

No. 10. *Igneous Rocks and Circulating Waters as Factors in Ore-Deposition.* By J. F. Kemp. This paper continues the discussion of the connection of vein-forming waters with igneous magmas, giving the author's reasons for thinking that Van Hise's final arguments, as presented in the discussion of previous papers, failed to afford an adequate explanation of vein-phenomena through the agency of meteoric waters alone. As will be observed, he inclines to the view that ore-deposits are likely to occur where some intrusive rock charged with metallic material has entered the earth's crust and imparted its

material to up-rising mineral waters, and that deposition in such cases has ceased, not, as maintained by Van Hise, because of cementation, but because the stimulating cause—the heat of the intruded body—became exhausted. He also differs with Van Hise with regard to the abundance of veins, and the universal and uniform occurrence of ground-water within the earth's crust.

No. 11. *A Consideration of Igneous Rocks and Their Segregation or Differentiation as Related to the Occurrence of Ores.* By J. E. Spurr. This is a recapitulation and analysis of arguments recently brought forward in favor of what may be called a magmatic theory of ore-genesis and of the facts that support it, together with certain views peculiar to the author, especially with reference to the magmatic origin of certain gold-bearing quartz veins. His final conclusion is "that the origin of metal-producing districts as contrasted with barren districts is, in most cases, due primarily to magmatic segregation, and that an important class of ore-deposits is due directly to this." Most workable deposits, however, he admits to be due to subsequent concentrations, often several times repeated, through the agency of water acting either chemically or mechanically. Like some others, Mr. Spurr has in this paper misconceived the meaning of the word "occlude," assuming it to be equivalent to "squeeze out," whereas it really means to "shut in" or "absorb."

No. 12. *The Chemistry of Ore-Deposition.* By W. P. Jenney. This is an elaborate compilation of data with regard to the influence which the various forms of carbon found in the rocks may have had in the precipitation of the metals in ore-deposits from their solutions, supplemented with actual observations by the author, mainly in the lead-zinc deposits of Missouri and of Tintic, Utah.

The reducing power of organic matter of any kind has been recognized from the earliest conceptions of the genesis of ore-deposits; and Dr. Jenney has rendered a valuable service in showing the great extent to which, under one form or other, it is found in nature in connection with them. There will probably be geologists who will question whether, in all instances quoted by him, this has been the only, or even the main, agent in the formation of the sulphide-deposits mentioned. Its action

is unquestionably reducing; but that a substance has been reduced implies that it was primarily in an oxidized condition. That this was the case for the secondarily-enriched material is undoubtedly true; but for primary mineral deposits the assumption seems hardly authorized.

No. 13. *Ore-Deposits Near Igneous Contacts.* By W. H. Weed. This is an attempt to make a genetic classification of ore-deposits, the majority of which the author believes to be, primarily, direct emanations from igneous bodies. Such attempts, when conscientiously and thoroughly made, serve a useful purpose in bringing together for discussion the evidence in favor of the views advocated; but it is questionable whether this classification of metamorphic contact-deposits, made before there has been time for accurate and extended studies of any great number of such deposits, has really advanced our knowledge of them to any considerable extent; for it means the establishing of a standard which nature is expected to follow, whereas, the reverse method is the only one which can yield sound and permanent results.

No. 14. *Ore-Deposition and Vein-Enrichment by Ascending Hot Waters.* By W. H. Weed. This paper treats of a phase of secondary enrichment which, though normally included in the original statement of this theory, had thus far received but little attention—namely, enrichment by ascending waters, or differential deposition. It is a phase which is less susceptible of actual observation or demonstration than that by descending waters; hence the data bearing on this subject which Mr. Weed has here gathered are of great importance, and deserve to be put on record.

No. 15. *Basaltic Zones as Guides to Ore-Deposits in the Cripple Creek District, Colorado.* By E. A. Stevens. This paper presents the conclusions of the author, who had been professionally connected with various Cripple Creek mines, with regard to the effects of recent dikes upon ore-concentrations in that district. They differ in some respects from the theories previously maintained, and may not be confirmed by future studies; but they are suggestive and worthy of consideration.

No. 16. *The Geological Features of the Gold-Production of North America.* By W. Lindgren. The portion of the paper included in this volume presents the practical application of

the knowledge with regard to ore-deposition thus far obtained on this continent, and a classification of deposits of gold, primarily by relative age and also to a certain extent by method of genesis, and gives the practical conclusions as to future production that may be drawn therefrom. Coming from one so well qualified for the task, both by ability and by the advantages of official position, as Mr. Lindgren, these conclusions may be considered as most important and authoritative.

No. 17. *Osmosis as a Factor in Ore-Formation.* By H. B. Gillette. This paper discusses a force, the possible importance of which in the process of ore-deposition has not received the attention from economic geologists in general which it seems to deserve. Already, in 1892, Dr. George F. Becker[3] had called attention to the possibility that osmosis might explain the differing action of the same mineral-bearing solutions on the interior of a vein and the adjoining wall-rock, only the solutions of the gangue-materials being able to penetrate the latter. Later, experimental tests were made by Dr. E. A. Schneider[4] on colloidal sulphides of gold, carrying out the idea in a modified form. Lindgren has practically applied it in his discussion of the vein-deposits of Nevada City and Grass Valley, Cal.,[5] and of Cripple Creek, Colo.[6]

Mr. Gillette does not refer to these earlier investigations, but makes the suggestion that metasomatic replacement—for instance, of limestone by kaolin—is a physical rather than a chemical process, and that for every particle deposited by crystallization a particle of country-rock may be dissolved.

No. 18. *The Ore-Deposits of Sudbury, Ontario.* By C. W. Dickson. The genesis of these important nickel-bearing pyrrhotite-deposits has been the subject of repeated discussion ever since their discovery. The most contradictory conclusions have been reached by different geologists, whose acknowledged ability entitled them to equal scientific credence. The view expressed in this paper differs essentially from those of the majority of writers on the subject, especially the Canadians;

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[3] *Mineral Resources of the United States*, p. 156 (1892).

[4] *Bulletin No.* 90, *U. S. Geological Survey* (1892).

[5] *Seventeenth Annual Report, U. S. Geological Survey*, Pt. II., p. 183 (1896).

[6] *Professional Paper No.* 54, *U. S. Geological Survey*, p. 229 (1906).

but it presents the result of most careful microscopic study; and the paper contains so full, and apparently methodical, a statement of previous investigations, not only of these, but of cognate deposits, that it has been thought best to give it in full, since the facts are important and worthy of credence, whatever may be the reader's opinion of the conclusions reached by the author. Even if, as claimed by some of those who hold the opposite view, the phenomena here presented are found in only a small portion of the area exploited, that fact does not justify their being disregarded. A preliminary magmatic concentration does not preclude a subsequent concentration by some form of metamorphic action. It may never be possible, where both these processes have been active, to determine the exact proportion of the resulting deposit which may be due to either, that is, which played the greater part in its formation; but it would hardly seem proper to characterize a deposit as a magmatic concentration if it has been brought to its present condition of an economically-workable deposit through the agency of subsequent aqueous concentration.

No. 19. *The Genesis of the Copper-Deposits of Clifton-Morenci, Arizona.* By W. Lindgren. This is an admirable supplement to his earlier paper on contact-metamorphism in the previous volume. It contains the genetic conclusions derived from an actual and detailed study of a most typical group of contact-metamorphic deposits, in which he has been able to verify in nature many of his previous theoretical conclusions—notably that of the actual contribution of material by intruding igneous magmas to the intruded rocks, as well as many new and valuable data as to the phenomena of contact-metamorphic copper-deposits.

No. 20. *The Copper-Deposits of San Jose, Tamaulipas, Mexico.* By J. F. Kemp. This is a description of contact-metamorphic deposits of copper in limestone in the periphery of an intrusion of diorite-porphyry. It contains a discussion of the chemical processes by which the lime silicates, mainly garnets, are formed, and of the origin of the material which enters into their composition—whether it can all be accounted for as originally contained in the limestone, or whether some portion must have been added during the intrusion of the igneous magma. This paper thus forms a supplement to that of Mr.

Lindgren on Clifton-Morenci, and, though descriptive, constitutes an addition to our knowledge of the general process of contact-metamorphism.

No. 21. *Magmatic Origin of Vein-Forming Waters in Southeastern Alaska.* By A. C. Spencer. This is an argument in favor of the magmatic origin of vein-forming waters in that region, following the suggestion of Lindgren that the gold-quartz veins of Victoria, Australia, and of California, have been deposited chiefly by water originally contained in a granitic magma, possibly aided to a certain extent by atmospheric waters.

No. 22. *Genetic Relations of the Western Nevada Ores.* By J. E. Spurr. This paper ascribes a magmatic origin to the ore-bearing waters which have produced the gold- and silver-deposits of western Nevada, and, in the Silver Peak district, even suggests that the gold-bearing quartz veins are siliceous phases of the cooling alaskite.

No. 23. *Are the Quartz Veins of Silver Peak, Nevada, the Result of Magmatic Segregation?* By J. B. Hastings. This is a criticism of Mr. Spurr's views, as applied to the Silver Peak quartz veins in the foregoing paper.

No. 24. *The Occurrence of Stibnite at Steamboat Springs, Nevada.* By W. Lindgren. This is a record of recent additional experimental observations by the author on the processes going on at Steamboat Springs, Nevada, where Becker had in 1885 proved that metallic sulphides were actually being deposited by hot thermal waters. It is interesting as noting the changes that have apparently taken place in the deposits within 16 years.

No. 25. *A Summary of Lake Superior Geology with Special Reference to Recent Studies of the Iron-Bearing Series.* By C. K. Leith.

No. 26. *The Geological Relations of the Scandinavian Iron-Ores.* By Hjalmar Sjögren.

These papers, Nos. 25 and 26, contain respectively summaries, by men especially well equipped for the purpose, of the geology of the two great iron-ore regions of the world,—the Lake Superior region of North America and the Scandinavian peninsula in Europe. While not primarily genetic, they pre-

sent summaries of the geological relations of the respective deposits which involve a discussion of their genesis.

It is interesting to contrast the broader outlines of genesis of these two greatest known concentrations of metallic ores in the world. They both occur in the very oldest rock-series that have yet come under observation and study, and are themselves, in the main, of pre-Cambrian age, though they may have suffered some further concentration in more recent times. They are considered to be essentially concentrations by oxide-laden surface-waters of iron-material, originally disseminated in the form of carbonate, silicate, or even oxide, in the beds of the sedimentary series in which they occur, and are thus what the European geologists would classify as sedimentary in origin. It is true that these primary constituents are considered by Van Hise to have been derived in a last analysis from decomposing igneous rocks, out of which they were dissolved or abraded by sea-waters, while the actual process that has made them of economic value has been later than sedimentation, and entirely independent of it.

The sedimentary origin formerly maintained for a large proportion of the Scandinavian ores is now considered to be impossible, since metasomatism, the importance of which has been more readily recognized by the Swedish than by any other European geologists, is shown to be the process by which they have been formed, through the agency, however, of deep-seated rather than surface-waters. Although the Scandinavian iron-deposits are here divided into several distinct types, they are all more or less distinctly connected with igneous eruptives. Some are considered to be magmatic segregations; the greater part are some form of pneumatolytic formation, of which the extreme type is the contact-metamorphic deposit in limestone. One or more of the lime silicates, garnet, amphibole, etc., are very common associates of all the ores. Secondary alteration and concentration by surface-water is considered to have played but a very subordinate part, if any, in producing the present deposits.

No. 27. *The Formation and Enrichment of Ore-Bearing Veins.* By George J. Bancroft. This is a discussion, by an experienced mining engineer, from the point of view of his own personal observations in Western mining-districts, of various points in the theories of genesis from aqueous solutions presented in

the previous papers. The main conclusions peculiar to his point of view, are that veins are formed in relatively short periods, and from rich or concentrated solutions.

No. 28. *The Distribution of the Elements in Igneous Rocks.* By H. S. Washington. This is a discussion of the relative amount of the elements, as shown by the improved modern methods of rock-analysis, that go to make up the ore-deposits found in different varieties of igneous magmas. From the point of view of the petrographer and chemist, this is an important inquiry; and though at present it yields but few results of actual economic bearing, it is significant of what may be expected from further research along these lines. It is noteworthy that while the average water-content of crystalline rocks is not over 2 per cent., this percentage may be carried up to 12 in fresh glassy lavas, from which the water was unable to escape, owing to the rapidity of solidification.

No. 29. *The Agency of Manganese in the Superficial Alteration and Secondary Enrichment of Gold-Deposits of the United States.* By Prof. W. H. Emmons, Copperhill, Tenn. This paper forms a fitting close to the series. It is a thorough examination and discussion of the doctrine of secondary enrichment, as applied to the single metal, gold. It had already been noticed that there are gold-deposits which have evidently been, and others that apparently have not been, enriched by surface oxidizing waters. The author and his assistants, by a series of chemical experiments, have discovered the cause of this difference, and thus contributed an important scientific addition to the doctrine of secondary enrichment, which, in practice, should enable the mining engineer to determine whether a given gold-deposit is secondarily enriched; whether it is capable of producing valuable placers by disintegration; or whether neither condition can be expected. It also accounts for transfers of gold from a higher to a lower horizon in certain classes of deposits. This is the type of investigation to which we may look hereafter for the most valuable results in furtherance of the science of ore-genesis.

BIOGRAPHICAL NOTICE OF SAMUEL FRANKLIN EMMONS.

BY GEORGE F. BECKER, WASHINGTON, D. C.

(San Francisco Meeting, October, 1911. *Trans.*, xlii., 643.)

A MERE record of Emmons's professional career would very inadequately represent the man. That he was eminent we know, and our successors will realize in due time; but they must depend upon us for knowledge of a singularly wholesome, modest, unselfish personality, and of a character that did honor to a profession in which trustworthiness is indispensable. Those members of the Institute who met Emmons are his friends, and I never knew one of these who was not the better for that friendship.

Emmons was born in Boston, Mar. 29, 1841, the son of Nathaniel H. and Elizabeth (Wales) Emmons, and was named Samuel Franklin after an ancestor who was of the same family as Benjamin Franklin. He took the degree of Bachelor of Arts at Harvard in 1861, and soon afterwards went abroad to complete his education. From 1862 to 1864 he attended the courses at the École Impériale des Mines at Paris, Élie de Beaumont and Daubrée being among his professors. The year 1864–1865 he spent at Freiberg under Cotta and other famous teachers; after which he spent another year in traveling through Europe. Like many other renowned geologists, he approached his ultimate profession from its economic side, and was thus from the first imbued with a sense of high responsibility in the promulgation of scientific opinions or conclusions. With hypotheses which were interesting merely because they were ingenious or even plausible, he would have nothing to do.

In 1867 he joined the Geological Exploration of the Fortieth Parallel at its organization under Clarence King, serving at first as a volunteer, but soon receiving a regular appointment. This expedition was the first one of purely geological character sent out by the United States government. As Emmons has shown in his admirable presidential address on "The Geology of Government Explorations," its work was founded

on a complete and comprehensive plan, adopted before taking the field, and systematically followed in all essential features during the ten years of its existence. This plan aimed at the highest efficiency compatible with prompt completion. It was important from every point of view that the broad outlines of the geology and mineral resources of the belt of country to be opened up by the completion of the transcontinental railway should be made known as soon as practicable. To execute a final, detailed survey under such conditions was impossible; and for this reason the work was called an exploration, but as a first approximation to the truth the intention was to make it irreproachable in methods and in symmetry. The best experts to be had were secured; contour-mapping as a basis for geological work was introduced for the first time in this country;[1] and, when lithological collections had accumulated, a well-known European petrographer was engaged to discuss them by the new microscopic methods, then wholly unfamiliar to American geologists. Emmons's associates as assistant geologists were our late eminent colleague James D. Hague, and his brother, Mr. Arnold Hague. The expedition started in 1867 from Sacramento; and it will help our younger brethren to grasp the changes which have taken place in the civilization of the West to be reminded that an escort of 30 regular soldiers was needed in that year to protect the civilians from hostile Indians.

To realize how hard the men worked, it is only needful to glance at the Fortieth Parallel memoirs and maps, but shooting was an available recreation, and afforded a legitimate means of varying a monotonous diet. There was one particularly good bear-story which Dr. Raymond has recorded in his notice of King in Emmons's own words.[2] Of this Dr. Raymond writes me:

"King, who always reaped the glory which his splendid audacity deserved, killed the bear; but the story shows that Emmons was posted at the other end of the passage where the wounded bear would have come out, if King's shot in the dark had not been fatal!"

One of the rules of the Fortieth Parallel Survey was, that its

[1] Capt. John Mullan's Report on the Construction of a Military Road, 1863, contained contour sketch-maps surveyed and drawn by Theodore Kolecki.

[2] *Trans.*, xxxiii., 633 (1902).

members should be as civilized as practicable, especially at meals. The men believed in a good and varied diet, well-cooked and served; and, when the accounting-officers of the War Department demurred at passing a bill for currant-jelly, they were met with a threat to charge up at the rate of beef the venison furnished by members of the mess. By such means the geologists preserved both their digestion and their adaptability to social life at centers of civilization, in which every one of them took a prominent part in later years.

Two episodes in the history of the Exploration of the Fortieth Parallel deserve mention. In 1870, the appropriation-bills passed too late for a regular season of field-work, and King decided on an examination of the extinct volcanoes of the Cascade range. He and Emmons ascended Mt. Shasta, and there found the first glaciers recognized within the limits of the United States. Later, in the same autumn, Emmons made the ascent of Mt. Rainier, where he found much more extensive glaciers, which he has very graphically described. Emmons made no claim to the first ascent of this great peak, recognizing that it had been scaled two months earlier by Gen. Hazard Stevens; but our colleague, who was accompanied by Mr. A. D. Wilson, was the first to bring from this dormant volcano valuable information on its topography, geology, and glaciology. During the same season Mr. Arnold Hague ascended Mt. Hood, where he too discovered typical glaciers.

In 1872 Emmons took part in the exposure of the famous diamond swindle. Though strong efforts were made to keep secret the locality of the alleged diamond "discovery," King made out that it must be in a region which Emmons had surveyed. They set out together to investigate, and Emmons was able to lead the little party to the scene of the crime in Vermillion Creek Basin, Wyoming. This had been selected by the swindlers because it was in a nearly waterless region, from which almost any expert would retreat at the first possible moment. A great financial disaster was averted by the detection of this fraud, and it is doubtful whether King could have achieved the disclosure without Emmons's knowledge of the country.

In King's Exploration, Mr. Arnold Hague and Emmons had charge of the descriptive geology. In 1870 Emmons had con-

tributed a chapter on the Toyabe range and some minor notes to Vol. III. (Mining Geology). With these exceptions, and that of his description of Mt. Rainier, all his work on that survey is contained in Vol. II. (Descriptive Geology), printed in 1877, and containing nearly 900 pages. In the letter of transmittal by the authors the limitations of the work are thus emphasized:

"It will be readily understood by the reader, from the very title of the work, that this does not claim to be a systematic survey like those of Europe, based on accurate maps, but is rather a geological reconnaissance in an unknown and often unexplored region, where geology and topography had to go hand in hand, and that therefore, while details were often, from the necessities of the case, somewhat neglected, it was the general bearing of the leading geological facts that was most constantly in our minds."

Now-a-days, I suppose, no one would think of reading this volume through, though it remains an important book of reference. In 1877, however, it was full of news, and Gerhard vom Rath, to whom geology (directly and indirectly) owes so much, told me in 1883 that it was the interest the Descriptive Geology aroused in him which led him to visit the United States. It was, I remember, the first work I ever reviewed; and I greatly enjoyed the task.

In accordance with the plan of the Exploration of the Fortieth Parallel all the men had constantly to guard against two temptations, one being to follow out their problems by detailed studies at an undue expenditure of time, and the other to gain time by slighting important matters in which they might happen to feel relatively slight personal interest. There can be no doubt that they displayed great self-control; and in my opinion the result was an unrivaled model of a preliminary survey in an unknown region.

It should not be forgotten that the topographic and the geologic reconnaissances were executed at substantially the same time, so that the geologists rarely had maps in the field on which to record their work. This involved keeping in mind and in note-books a vast number of detailed observations systematically co-ordinated and of a prescribed standard in respect to generality. Ten years of this sort of thing gave Emmons an unusual command of details, and power to marshal them mentally without extraneous aid. In short, it was the

training in descriptive geology, as he practiced it, which enabled him subsequently to deal with the complexities of Leadville.

With the completion of the Descriptive Geology in 1877, the connection of its authors with the Fortieth Parallel ceased. For the next two years, Emmons devoted himself to a cattle-ranch near Cheyenne. The country was still unfenced, and great profits were possible in this business, while the active, out-door life suited Emmons's temperament and habits. Even after his return to scientific life, he retained his interest in this ranch for some years, and kept there a pack of Scotch deer-hounds with which he hunted.

In March, 1879, the government organizations which had been carrying on geological reconnaissances were merged in the present United States Geological Survey, and King was appointed Director, taking his oath of office on May 24. As a matter of course, a position was offered to Emmons, and he qualified on August 24.

In the autumn of that year King summoned Emmons and me to Washington, in order to prepare schedules for the examination of the precious metals industries under the Tenth Census, a task undertaken by the Survey as a matter of courtesy to the Census Bureau and as germane to its own office. As soon as Emmons arrived, I called upon him; and when, an hour later, King entered the room to introduce us, we were already friends. Such we always remained without a single misunderstanding.

It was for each of us a busy and interesting period, and in later years a favorite subject for reminiscence. Emmons, though of course strong on general geology and lithology, was rusty in technical mining and metallurgy, which I had been teaching; and while I had a considerable familiarity with ore-deposits, my knowledge of general geology and lithology was elementary. Indeed, on joining the Survey, I had stipulated with the Director that he should call upon me only for mining and metallurgical reports. Thus the preparation of schedules led to many instructive discussions, carried on with the utmost freedom and good-will. We worked hard and long. We were in almost daily consultation with King, who was well informed on the whole subject, but I do not remember

that he ever made any material change in our plans; and we also had prolonged sessions with Gen. Francis A. Walker, Superintendent of the Census, who was thoroughly agreeable and agreeably thorough.

Life was not all work, however. John Hay, then Assistant Secretary of State, and King had at Wormley's a private dining-room, which they invited Emmons and me to share with them. I doubt whether there ever was table-talk more brilliant than that to which we listened in that room. Neither Emmons nor I said much, but we egged on the other two, and laid little plots to get them started on matters we desired to hear discussed. King and Hay were intimate friends, and particularly well-fitted by differences in temperament and experience to complement one another in conversation. Though Hay rarely indulged in humor and was not a man of buoyant spirits, he was never commonplace or ponderous. He was gifted with true wit, whose gleams showed even familiar relations in new aspects and revealed relationships among less familiar things. He offered, but never obtruded, suggestive reflections gracefully epitomized, and in this intimate companionship disclosed the grasp of affairs and breadth of view which were to make him a great Secretary of State. As for King, hear Hay!

"He was inimitable in many ways: in his inexhaustible fund of wise and witty speech; in his learning, about which his marvellous humor played like summer lightning over far horizons; in his quick and intelligent sympathy, which saw the good and amusing in the most unpromising subjects; in the ease and airy lightness with which he scattered his jewelled phrases; but above all in his astonishing power of diffusing happiness wherever he went."[3]

Had these wonderful dinners not been so entertaining they might have been considered as equivalent to a post-graduate course in liberal education. They exerted a lasting influence on Emmons and me, expanding our views and adding symmetry to our standards of thought and achievement.

It was while we were engaged on the Census schedules that King completed his plans for the investigation of ore-deposits, and placed the work in our charge by the orders quoted in Emmons's introductory chapter to this volume. I was reluctant to accept the responsibility, and I should have persisted in

[3] *Clarence King Memoirs*, p. 131 (1904).

refusing it, had not Emmons urged me to make the attempt, assuring me in the kindest manner of his co-operation and assistance, so far as circumstances might permit. He began to cram me immediately; and, during the field-work in Leadville and on the Comstock, we were in constant correspondence on every phase of both problems.

Early in 1880, each of us had to select and instruct a staff of young mining engineers who were to collect the statistics and technological data under the Census, while at the same time we organized and commenced our geological field-work; in fact Emmons began on the geology of Leadville just before the New Year.

What little is to be said of the Census work may be said here, although it was not completed until Emmons's abstract of his Leadville report had been printed. The purpose of the Statistics and Technology of the Precious Metals was to furnish mining-men with accurate data of production and a record of technical practice in the year 1880, together with such an outline of the geology of the mining-districts as could be prepared from material already published, supplemented by the information derived from the reports and collections sent in by the experts in the field. It was a harassing piece of work; and it is needless to say that some districts were more competently reported than others; but under the circumstances, and on the whole, the authors were fairly satisfied with the result. Its value would have been enhanced by prompt publication. By working at night and on holidays the manuscript and maps were completed and transmitted on Feb. 8, 1883; but more than a year elapsed before the first galley-proofs reached us; and in the meantime the maps had disappeared from the Census Office. I remember exactly how we felt!

After King retired from government work, I was placed in charge of the Statistics and Technology of the Precious Metals, so that for a time I had the honor of counting Emmons nominally as my assistant; but of course we worked together as before, and no question of subordination was allowed to arise. When it came to deciding the order of our names on the title-page, however, he said I was in charge and should come first, while I maintained that he, as the senior and more experienced, should take precedence. As neither would be convinced, I

proposed deciding the matter by the turn of a coin. Thus we settled it, standing by the statue of Jackson, in the city of Washington. He won the toss and I my way.

In spite of the labor involved in gathering statistics under the Census, Emmons pushed the examination of the geology of Leadville so energetically that he was able to close his office at the camp on Apr. 1, 1881, and to transmit his Abstract of a Report on the Geology and Mining Industry of Leadville on October 20 of that year. This abstract, which appeared in the *Second Annual Report of the Director of the United States Geological Survey*, is a memoir of 87 pages and contains the principal results of the investigation. The publication of the *Monograph* was delayed by various causes till 1886; but his main conclusions were not changed in the intervening time.[4] In the field-work he was assisted by Ernest Jacob, Whitman Cross, and W. H. Leffingwell as geologists, and by W. F. Hillebrand and Antony Guyard as chemists.

Emmons's views of the Leadville ore-deposits, up to the time of the publication of his *Monograph*, may be condensed into the following statement: Prior to oxidation, the ores consisted of sulphides of lead and silver, zinc and iron, which were deposited by substitution for country-rock, this being as a rule limestone or dolomite, but in some instances siliceous in character. The ore reached the deposits as hot aqueous solutions at high pressures, and came from above. The temperature was due to the depth (about 10,000 ft.), and the magmatic heat of the intrusive porphyries. The water was of meteoric origin and derived its metallic content, perhaps wholly but demonstrably in part, from masses of porphyry which were not necessarily in juxtaposition with the ore. The principal deposition took place at the upper surface of the blue Carboniferous limestone.[5]

Twenty-one years later he returned to the subject with Mr. J. D. Irving in a paper on the Downtown District;[6] and the

[4] In the *Abstract* Emmons regarded the ores as derived from the porphyries, while in the *Monograph* he considered them as "mainly" derived from this source.

[5] See Abstract, *Second Annual Report, U. S. Geological Survey*, p. 234 (1882). Geology and Mining Industry of Leadville, p. 584 (1886). Also, *Trans.*, xv., 138 (1886–87).

[6] *Bulletin No.* 320, *U. S. Geological Survey* (1907).

only important change he was obliged to make was an addition rather than a correction. Developments in the intervening decades had shown that many, instead of few, ore-bodies existed within the mass of the Carboniferous limestone (not merely near its upper surface), and also in the Silurian limestone. Meanwhile, however, the subject of juvenile or magmatic waters, first investigated by Charles Sainte-Claire Deville and other French *savants*, had been actively studied and discussed, so that in 1907 questions arose as to the possible participation of such waters in the genesis of the Leadville deposits. How far the original sulphides at Leadville were deposited from juvenile waters, and whether instances of deposition as a feature of contact-metamorphism were to be found there, were still unknown.

This paper by Emmons and Irving was, in fact, a partial abstract in advance of a monograph by the same authors, in which the entire Leadville work was to be revised. Fortunately the volume was so nearly completed before the senior author's death that Mr. Irving is in a position to finish it within a few months. How far it will answer the questions which were still open in 1907, I do not know.

Leadville presents the most intricate problem of mining-geology ever attempted; for the structure is as complex as the chemical history of the deposits. Emmons brought to the study of this district a mind trained to carry a vast number of observations in due relation to one another; and this enabled him to execute a truly monumental work. His *Monograph* has been of enormous importance to miners, for experience has shown that its predictions were substantially correct; it has been of material advantage to the Geological Survey as an evidence of what geology can do for industry; and it has set an example to younger geologists of the mode of treatment proper to such a problem. The revision of this great work after the lapse of 30 years worthily closed his career.

Having concluded that the Leadville ores were deposited by substitution, mainly for limestone, Emmons was led to study instances of the replacement by ore of other rocks. Indeed, even in his Leadville Abstract of 1882, he had recognized limited occurrences of ores substituted for siliceous rocks. Cases of this kind had been described in Europe by Groddeck

and others; but in this country only the native copper of Lake Superior had been recognized as pseudomorphic by Mr. Pumpelly. Emmons soon found abundant evidence capable of interpretation as indicating replacement or metasomatism in a wide sense; that is to say, he found much ore in situations from which even siliceous rocks or minerals had been removed. To cover them all, he defined metasomatism as an interchange of substances, but not necessarily molecule by molecule.

This breadth (perhaps I ought to say looseness) of definition was unavoidable unless he had been willing to postpone for years the announcement of his results; for convincing detailed proof of the various processes active in the alteration and impregnation of wall-rocks requires prolonged and difficult chemical and microscopical investigation. Among engineers the idea, new to many of them, immediately became popular, too popular, in fact; and at one period there was danger that all deposits would be set down without due proof as cases of replacement. Some, however, were left to protest; and, after a few years, the matter was reduced to proper proportions by Mr. Lindgren,[7] who, adopting as his criterion the principle that the theory of substitution of ore for rock is to be accepted only when there is definite evidence of pseudomorphic, molecular replacement, worked out his results with great labor and discrimination. There can be little doubt that as geological chemistry is elaborated the importance of deposition by substitution will be still further recognized, and that studies devoted to this subject will shed unexpected light on geochemical processes.[8]

Secondary enrichment of sulphide ores attracted attention

[7] *Trans.*, xxx., 596 (1900).

[8] Among the very first observations which I made on the Comstock lode was, that much of the pyrite in the wall-rock was pseudomorphic after ferromagnesian bisilicates. (*Geology of the Comstock Lode*, p. 210, 1882.) Emmons's studies on replacement led me to examine the quicksilver-mines very closely for pseudomorphic deposition of cinnabar. In spite of profound alteration of wall-rock, attended by other replacements, I found no instance of deposition of cinnabar by substitution for carbonates or silicates. These facts led me to suggest the dialytic or osmotic separation of ore-bearing solutions, a hypothesis which is thus indirectly due to Emmons. *Geology of the Quicksilver Deposits of the Pacific Slope*, p. 396 (1888), and *Mineral Resources of the U. S. for* 1892, U. S. Geological Survey, p. 156 (1893).

in Europe earlier than in this country. The relative affinity of the metals for sulphur was investigated as long ago as 1837, by E. F. Anthon,[9] but the first application to ore-deposits with which I have met is contained in Mr. Joaquin Gonzalo's admirable monograph on Huelva, issued in 1888. The secondary deposits of chalcopyrite (occasionally accompanied by other copper-compounds), and galena, as they are found at Rio Tinto, are described by the Spanish geologist as occurring along lithoclastic fractures in the mass of the pyrite. They are attributed to a process of segregation within the mass and to the reduction of sulphates percolating downward from the zone of oxidation.[10] Mr. J. H. L. Vogt, after personal examination, entirely assented to Mr. Gonzalo's views, and pointed out subsequently that secondary enrichment is the true meaning of that familiar old proverb: *Es thut kein Gang so gut, Er hat einen eisernen Hut.*[11]

Emmons's own studies on secondary enrichment were begun at Butte in 1896; and he freely discussed his results in private, though they were first published in our *Transactions* in 1900. In this paper he quotes from that of Vogt, issued the year before, but also sets in order a long series of observations of his own, which form an extremely important contribution to the subject. This is cognate to his other studies on replacement; for his idea of secondary enrichment might be paraphrased as the replacement of pyrite by the sulphides of other metals, especially copper.

The idea of secondary enrichment was in the air at the close of the last century, and had been very distinctly suggested in this country (for instance by Dr. James Douglas), though without sufficient substantiation. Almost simultaneously with Emmons's memoir appeared important papers by Messrs. Weed, Van Hise, and Lindgren.

It is not needful here to pass in review all of Emmons's work. A full list of his papers will be found at the end of this notice. All of them are as conscientiously elaborated as those

[9] *Journal für praktische Chemie*, vol. x., p. 333 (1837). See also E. Schürmann, in *Leibig's Annalen*, vol. ccxlix., p. 326 (1888).

[10] Mem. de la Comm. del Mapa Geológica de España. Descripción física, geológica y minera de la provincia de Huelva, por Joaquín Gonzalo y Tarín, pp. 217 to 220 *et passim* (1888).

[11] *Zeitschrift für praktische Geologie*, pp. 241 to 254 (July, 1899).

which I have selected for mention on account of their peculiar importance. On the other hand, a few remarks seem appropriate on the tendency and the development of the science which he so admirably represented.

When Clarence King planned the researches of the U. S. Geological Survey into the origin and nature of ore-deposits, and placed Emmons and me in charge of them, no one of us was in a position to appreciate the multifariousness and intricacy of the facts which these investigations would disclose; but before King's untimely death, the vastness of the task was manifest, as well as the necessity for improved methods of investigation and for experimental researches of the most fundamental character.

More than half of the great amount of information now available to mining-geologists is due to the use of the microscope, armed with which, the eyes of the generation now passing away have been a hundred times as sharp as those of their predecessors. But the microscope is not merely a powerful magnifying-glass; it is an instrument of moderate precision, whose use has familiarized us with quantitative measurement and stimulated us to demand exact methods of geological investigation.

It is not enough to know the facts, for these alone lead only to delusive "rules of thumb." We can and must attain a comprehension of the mechanical, chemical, and thermal processes which underlie the formation and distribution of ores, as revealed not only by the microscope, but also by every other available method of research. Many of the problems presented are of extraordinary difficulty, far exceeding in this respect most of those undertaken by professional physicists and chemists; but they are not insoluble; and the limits of our knowledge are extended year by year.

None of us have been more impressed with the necessity for such researches than was King, or even Emmons, who regretted all his life that he had not a better command of the exacter sciences. Let me pass the word on from them that the future of the science of ore-deposits depends on investigations of the utmost precision into the fundamental principles of geophysics. Physics and physical chemistry will be as indispensable to the mining-geologist of the future as mineralogy to the petro-

grapher or zoölogy to the palæontologist. It is a duty which the Institute owes to its founders, its members, and the world, to promote and foster research of this description; to advance as rapidly as possible the day when mining-geologists, no longer groping, will comprehend why ore-deposits are what we find them to be.

And now as to the man himself. There is not a geological society or even a mining-camp from Arctic Finland to the Transvaal, or from Alaska to Australia, where Emmons's name is not honored and his authority recognized; nor is there a society of which he was nominally an active member in which he was not really active and efficient. Thoroughness and good judgment characterized all he did. He had a very high sense of responsibility and rarely made his hypotheses public; yet his originality has enriched the science to which his life was devoted. In private life, he was modest to the point of diffidence, and many of his old acquaintances scarcely knew of his distinction; but none could long enjoy his acquaintance without becoming conscious of the kindness of his heart and the elevation of his character. He would not have known how to undertake an unworthy action, or how to do a selfish thing. His published investigations will live on as sources of knowledge and models of method; and in a similar circle his personal example will continue potent for good.

Emmons died painlessly and unexpectedly in his sleep on Mar. 28, 1911, the eve of his seventieth birthday. Thus fitly ended a career of useful labor faithfully performed.

Among the societies to which Emmons belonged, none appealed to him more than the American Institute of Mining Engineers. He joined us in 1877, was three times Vice-President, contributed many papers to the *Transactions*, and was always ready to assist in organizing our meetings. He was also a member of the National Academy of Sciences, the American Philosophical Society, the American Academy of Arts and Sciences, the Washington Academy of Sciences, the Geological Society of London, the Geological Society of America, the International Congress of Geologists, and the Colorado Scientific Society. He was elected an honorary member of the

Société Helvétique des Sciences Naturelles, and received the degree of Doctor of Sciences from Harvard and Columbia.

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No. 1.

The Genesis of Certain Ore-Deposits.

BY S. F. EMMONS,* WASHINGTON, D. C.

(Bethlehem Meeting, May, 1886. *Trans.*, xv., 125.)

IN a report upon the geology of Leadville and vicinity, which is still in the hands of the Public Printer, I have given, at some length, my conclusions as to the genesis of the remarkable silver-lead deposits of that region, and the data, gathered during a long and careful consideration, upon which my views were founded. In the brief abstract of this report, published in 1881, the bare conclusions are given, with but few of the facts upon which they were founded. Since that time, these conclusions have been variously criticised, and it has even been assumed that the views I expressed with regard to these deposits were intended as a theory of ore-deposits in general.

Had my final report been printed, no such misconception could have occurred; for, in that I explicitly disclaim any intention of general application of the theories there presented. Even in the abstract I am unable to find any statements which would justify such a conclusion.

Since my Leadville work, however, I have had further opportunities of examining ore-deposits, and have given the general subject much thought and study, and, as a result, I have made in my own mind certain generalizations, which, I am conscious, need the test of a far greater number of practical applications than I have yet been able to make, but which, I think, it may be well to present to the members of the Institute as suggestive, that their own observations may further prove or disprove them. I shall use my Leadville observations and the criticisms which have been made upon them as a sort of text for my remarks.

The salient facts, which I thought to have determined with regard to the Leadville deposits, which, as is well known, are silver-lead deposits in a dolomitic limestone, overlain and in

* U. S. Geological Survey.

part also traversed by various bodies of porphyry, are the following:

1. That they were deposited from aqueous solutions.

2. That they were originally deposited as sulphides, at a great depth below the rock-surface (probably 10,000 ft.); that, by subsequent dynamic movements and by erosion, they have been brought to their present position near the surface, and that, through secondary alteration by surface-waters, they have been changed to oxides, carbonates, and chlorides.

3. That the process of deposition was a metasomatic interchange between the minerals brought in in solution and the limestone—that is, that they were not deposited in already existing open cavities, but gradually replaced the limestone, from the channels through which they reached it outward.

4. That the solutions or ore-currents reached the present *locus* of the deposits directly from above and not from below.

5. That, whatever may have been the ultimate source from which the mineral components of the deposits came, the observed facts point to the neighboring eruptive rocks as the immediate source from which they were derived by the ore-bearing solutions which deposited them in their present *locus*.

I will take up these propositions in the above order, and, after discussing the criticisms which have been made upon them, see how far they may be applicable to other deposits than those of Leadville.

1. That the vast majority of ore-deposits have been deposited from solutions, seems to be now so generally admitted as to require no further discussion here. This view is held by most all American, English and German geologists, while the French may be considered to be those who still cling to the sublimation theory in the modified form which is based on the remarkable synthetic experiments of Sénarmont, Daubrée, and others. But, as one of their number admits,[1] this is practically only a variety of the solution theory, which assumes that pressure and heat, sufficient to vaporize water, are necessary to bring about a solution of the metallic minerals. That many deposits have been formed under conditions of great heat and pressure is most probable; that heat and pressure greatly

[1] A. De Lapparent, *Traité de Géologie*, p. 1170 (1883).

increase the solvent power of percolating waters is evident; but that heat and pressure are an absolutely essential condition of mineral solution cannot be maintained, since we see in nature many instances of mineral solution and deposition under ordinary pressure and by comparatively cold waters.

2. That the Leadville ores were originally deposited in the form of sulphides, and that, therefore, they would be found in that condition, when explorations should have been pushed in depth beyond the oxidizing action of surface-waters, was assumed by *indirect reasoning* at the time my abstract was written, since at that time no sulphide deposits had been found on the so-called "contact" in the region. Explorations made since that time have abundantly proved the correctness of the assumption. An interesting description of some of the more important sulphide bodies, and of a previously undiscovered fault, was read at the Chattanooga meeting by F. T. Freeland.[2]

That metallic deposits, with the single exception of tin-ores, pass into sulphides or some allied combination in depth has been so generally observed, that it has almost come to be an axiom in vein-geology that original deposition must have been in this form. Some supposed exceptions have been observed; but the distinction between an original and a secondary deposit is often so delicate that it requires a most thorough and searching examination to determine the point satisfactorily. The determination beyond the shadow of a doubt of an original deposit of these metals in an oxidized form would be of the utmost interest to science.

3. That the process of ore-deposition at Leadville was a metasomatic[3] interchange between the material of the country-rock and the minerals brought in in solution by the ore-currents, is a point upon which I particularly desired to insist, because it is either tacitly or explicitly assumed by most text books that all ore-deposits in limestones are the filling of pre-existing cavities. This assumption, like the one that fissure-veins were once open cavities reaching to an indefinite depth, is, it seems to me, the result of generalizations upon too few

[2] *Trans.*, xiv., 181 (1885–86).

[3] By metasomatic interchange, I understand an interchange of *substances*, but not necessarily molecule by molecule in such a manner as to preserve the original structure, form, or volume of the substance replaced.

facts. The facts that support it (the arrangement of the ore in layers parallel to the walls of the body, etc.) are so striking in the few cases where they have been observed, that they have received universal mention, while the far more numerous cases, where no such evidence of pre-existing cavity is found, have remained in most instances without comment, as regards this question.

Professor Le Conte[4] quotes me as saying that the ore at Leadville was "accumulated in hollowed-out channels in the limestone," evidently assuming this as so much of a foregone conclusion that he had not thought it necessary to read my statement of the diametrically opposite conclusion at which I had arrived. Now, I not only distinctly stated that I believed the ore was not deposited in already hollowed-out channels or pre-existing cavities, but I mentioned that the caves, which are so characteristic of limestone formations, were at Leadville formed after the deposition of the ore. I laid stress upon the relation of these caves to those bodies, not because it was the only or even the main proof of the statement I made, but because I thought it would appeal to those who consider all limestone deposits as filling cavities hollowed out by surface-waters. The most convincing proof of the statement to my own mind is, that, in a prolonged study of the various deposits, I found no single fact to furnish any evidence that the ore was deposited in an open cavity; and I hold that, in such a case, the burden of proof lies on the side of those who uphold the open-cavity theory. There is, however, a consideration which can be briefly stated and which affords conclusive evidence, if no other were present; namely, that the deposits were originally formed at a depth of about 10,000 ft. below the surface and before the strata were disturbed, and that, therefore, surface-waters could not have reached their *locus* to hollow out such cavities.

I find it difficult to understand Professor Newberry's criticisms of my views on this point. In the first place, he makes what seems to me a totally unwarranted assumption, that I consider that the Leadville deposits were formed by surface-waters. Then, in presenting his own views on the formation

[4] *American Journal of Science*, Third Series, vol. xxvi., No. 151, p. 18 (July, 1883).

of the Leadville deposits, he says, "they were deposited by substitution,"[5] and afterwards remarks that the fact that caves in the limestone cut across the ore-bodies "has no bearing on the question."

In a former article, The Origin and Classification of Ore-Deposits,[6] his meaning is less ambiguous, and I shall take this opportunity of criticising him in turn. One of the divisions of ore-deposits there given by him is "chambers or pockets in limestone,"[7] of which he says: "From a study of them I have been led to add them to the catalogue of forms of ore-deposit as a distinct and important addition to those given by other writers." As examples, he quotes the Eureka, Richmond, Emma, Flagstaff, Kessler, and Cave mines, and (with the modification of their contact-character) the Leadville ore-bodies, of which he says they were "undoubtedly accumulated in vacant spaces formed by the solution of the limestone." The formation of the chambers in which he considers these deposits were formed, he compares to that of the Mammoth Cave, saying, "We must conclude that the chambers were formed, like modern caves, by surface-water." He then makes the following deductions as to the probable extent of such deposits: "They will not be found to extend to so great depth as the ore-bodies of fissure-veins, since the excavation of the limestone, if produced by atmospheric water, must be confined to the zone traversed by surface-drainage." He does not explicitly state what he considers to be the distinctive character of his important addition to the classification of ore-deposits, the want of information in regard to the true nature of which, he says, "has led to much litigation and heavy losses in mining." He surely cannot mean the irregular form of deposits in limestone, for this has been recognized from the very earliest days of mining, and has formed an important element in the classification of most writers on ore-deposits.[8] It would seem, there-

[5] The Deposition of Ores. *School of Mines Quarterly*, vol. v., No. 4, p. 341, *et seq.* (May, 1884).

[6] *School of Mines Quarterly*, vol. i., No. 3, pp. 87 to 104 (Mar., 1880).

[7] This division has been literally adopted by J. Arthur Phillips, in his *Treatise on Ore-Deposits* (1884).

[8] A criticism of this claim of novelty may be found in the *Engineering and Mining Journal*, vol. xxx., No. 1, p. 1 (July 3, 1880).

fore, that this distinctive character must consist in their having been hollowed out originally by surface-waters.

Surface-waters, as I understand the common use of the term, means those waters which have so recently left the surface as to still retain constituents common to waters now found at or near the surface (free carbonic and organic acids, chlorides, etc.), and which exert an oxidizing action; and from the above quotations this would seem to be his interpretation of the term also. Moreover, to dissolve out caves like the modern caves there should be a comparatively free flow of water and ready drainage to carry off the dissolved-out material, which could only be found at comparatively shallow depths. The waters which percolate through rocks, even at the greatest known depths, may in one sense be considered surface-waters; but at a certain depth below the surface these waters will have lost their free carbonic and organic acids and have become, so to speak, saturated and only able to dissolve out by actual interchange of their constituents with those of the rock through which they pass; in other words, no longer capable of leaving open caves. What this depth is, I am not yet prepared to say. It would differ greatly under varying local conditions. It would probably correspond with what is known as the "water-level" in Western mines, which is not generally below a thousand feet.

Now Professor Newberry's theory, or the one he here adopts, for it can hardly be considered original with him, involves a sort of see-saw movement for the rocks inclosing each deposit, which, though not impossible, seems from a geological standpoint highly improbable. He admits, with other geologists, that the original deposits were in the form of sulphides, and that the oxidized condition, in which the ores he speaks of are now found, is due to the action of surface-waters; hence, as originally deposited, they must have been below the reach of surface-waters. But the cavities in which they were deposited were formed by surface-waters; hence, the rocks inclosing the ore-deposits must have been once so near the surface as to have been hollowed out by these waters; then have been depressed beyond their reach, so that the ore-bearing solutions which deposited their contents in the caves were protected from oxidizing action, and then again raised to their present position,

where the surface-waters have changed their sulphides to oxides, and hollowed out a new set of caves. When I say raised and depressed, I mean not necessarily actual but only relative movement, as referred to the surface of the earth; this surface might itself have been raised by the accumulation of deposits over the rocks, and these accumulations again removed by erosion, so that the result would be accomplished without actual movement of the inclosing rock.

In such an assumption, I hold, one is not justified, unless he can find some evidence of it in the geology of the region involved. In Leadville there is none. The rocks inclosing the ore-deposits were never so near the surface as they are now, and dynamic action and erosion have gradually raised them from the depth of about 10,000 ft., at which the original sulphide deposits were formed. The same is true in a general way of the other examples quoted by Professor Newberry—the original deposits were deep seated, and, though the geology of the districts has not yet, in all cases, been studied in sufficient detail to afford as good estimates as to the depth of the original deposition as at Leadville, there is no evidence of any such relative oscillations as his theory would involve.

The practical application made by Dr. Newberry, though a logical deduction from his theory, viz., that deposits in limestone must be limited in depth to the zone traversed by surface-drainage, and therefore of less value than fissure-veins, illustrates the danger of *a priori* reasoning in geology, since it not only leads to geological improbabilities, but gives the influence of his name to a dangerous popular fallacy already too current among miners. I have shown in my Leadville work not only that the geological conditions there are such as to preclude the possibility of the formation of caves by surface-waters prior to the original ore-deposition, but that, in extent and in the quantity of ore contained in it, the Blue limestone, which may in one sense be regarded as a sort of horizontal vein, exceeds any known fissure-vein, not even excepting the famous Comstock lode. At Eureka, which is Professor Newberry's typical example, the exhaustive studies of J. S. Curtis, who came to the work with *a priori* views similar to those entertained by Professor Newberry, have shown not only that the ores were *not* originally deposited in open caves, but that caves formed by

surface-waters become less frequent in depth, and have nearly disappeared at 1,000 ft. from the surface. As the workings in this district are being rapidly deepened, a practical illustration of the depth at which cave-formation by surface-waters is still possible will soon be furnished. It will also be seen whether ore-deposition in this region stops at the limits of cave-formation. Even should it be found to do so, however, it would merely show a local coincidence, and not a logical consequence.

The possible application of the theory of the formation of ore-deposits by replacement or substitution is almost unlimited, and the limits of its actually demonstrated application are being every day extended, not only by studies of new districts, but by more careful and unbiased studies of old districts in which a different method of formation had previously been determined upon.

The process is most readily conceivable in the case of easily-soluble rocks, like limestone and dolomite; and, in point of fact, it is found that these rocks are the favorite receptacle of metallic deposits in mining-regions where the ores occur in the later stratified rocks, among which calcareous beds are abundant. It is also possible that in the older and more crystalline rocks, where the calcareous beds are of limited extent, metallic deposits occurring in large masses, like those of iron, may have so completely replaced the calcareous material that little or no trace of it remains. The old theory that iron-ores in the crystalline rocks are of eruptive origin is generally abandoned at the present day. The few geologists who still maintain this origin for individual deposits are doubtless influenced in their opinion by respect for views formerly advanced; while among those who come to the study with a mind free from preconceived ideas, and who push their examinations with sufficient thoroughness and detail, I have known of none of late years who have adopted the eruptive theory. The most striking instance that has come to my notice is that of the famous specular iron-ores of the island of Elba, which, when I was a student, were held as the most typical example of eruptive or sublimation deposits. These deposits were visited by the most prominent geologists of Europe; but, among them, Vom Rath, in 1870, was the first to doubt the

eruptive origin of the ores, which he showed in certain portions was impossible. The island has been systematically studied and mapped by the Geological Survey of Italy; and B. Lotti, the geologist in charge of this work, after a careful study of all the evidence and of the views held by those who have gone before him, but whose observations were necessarily less complete and exact than his own, decides that they must have been formed by replacement. The following is a literal translation of his conclusions:

"We may therefore reasonably conclude that the iron-deposits of Elba and their analogues, both of iron and of other metals, on the neighboring continent (excepting those connected with the serpentines) are formed by aqueous solutions of the metals, which found an easier passage for their subterranean circulation, and perhaps also for reaching the surface, between rock-masses of different nature, and deposited the metallic minerals which they held in solution when they met favorable conditions; that is, either in proximity to the surface or in contact with calcareous rocks with which an interchange of materials took place, and this in conformity with the law that the more easily soluble minerals are replaced by those that are less soluble. If the waters contained, besides the bicarbonate of iron, sulphydric acid also, there resulted a precipitate of sulphide of iron."[9]

As a reaction against the eruptive theory, it has been recently held[10] that all deposits of iron of whatever age have been formed, like the bog ores now forming, by surface-precipitation, and that they were therefore actual sedimentary beds originally, but in many cases have been altered by later metamorphism. This going to the other extreme is, it seems to me, as dangerous as the former *a priori* reasoning; and, as I read the descriptions of many of our iron-deposits, such a contemporaneous sedimentary origin for them would be impossible.

The theory of the formation of ore-deposits by replacement, as opposed to that by the filling of pre-existing cavities, may, however, be applied to deposits in rocks which are not so

[9] *Descrizione Geologica dell' Isola d' Elba*, p. 232 (1886).

[10] J. S. Newberry, The Genesis of Our Iron-Ores, *School of Mines Quarterly*, vol. ii., No. 1, pp. 1 to 17 (Nov., 1880).

readily soluble as limestone, in which cases the percolating solutions would have first attacked the relatively more soluble among their constituents. Very many so-called fissure-veins in crystalline rocks are formed by percolating waters, circulating along joints, shrinkage-cracks, fault-planes, or zones of crushed rock, which have filled the interstitial spaces and replaced the materials of the adjoining country-rocks to a greater or less extent by the materials they held in solution, but are not the filling of any considerable open cavities.

The comb-structure of veins, on which the early geologists founded their theory that a vein was necessarily the filling of a pre-existing open cavity, is of comparatively rare occurrence. As early as 1869 Richard Pearce observed in the classic veins of Cornwall that the gangue-material, instead of being a foreign material brought from a distance, was the more or less completely altered country-rock, and his views have been confirmed and further illustrated by the investigations of C. Le Neve Foster, his successor in that district. The evidence obtained by my own observations, together with the data gathered during the investigation of the precious-metal deposits of the Rocky mountains under the Tenth Census, led me to conclude that the majority of the deposits there are such replacement-deposits; and I have not yet seen satisfactory evidence of a deposit which consists essentially of the filling of any considerable pre-existing cavity by foreign material. Cracks or fissures must undoubtedly have existed, which determined the concentration of mineral solution along their course; but whether such cracks were to any great extent fault-planes, whose movement might have left large open spaces between the irregularities of their walls, seems questionable. The Comstock vein occupies a fault-plane, and its ore fills the interstitial spaces in the crushed material between the walls, but there was no filling of a pre-existing open cavity, as I understand it. In Leadville one of the most noticeable facts is that the fault-planes, which may be supposed to reach to great depths, have been found barren of ore except by secondary infiltration from surface-waters, or as attrition-material from pre-existing deposits, when the fault-line cut across such deposits.

In this connection I would remark that it seems to me that

the idea that a fissure-vein necessarily extends to an indefinite depth is another popular error, and not founded on good geological reasoning. Whatever the nature of the fissure along which the deposit has taken place, whether fault-plane, joint, or shrinkage-crack, there must be some mutual relation between its horizontal and its vertical dimensions. In other words, the study of structural geology shows that the length of such a fissure or crack must bear some proportional relation to its extent in depth, and the probability is that the latter must be less than the former. Now veins can generally be traced continuously for an extremely limited distance; the Comstock, which is probably one of the longest known, is traced only about 20,000 ft., and those which exceed 1,000 or 2,000 ft. are comparatively rare. As yet there are not sufficient data for establishing any numerical ratio between the depth and the length of mineral veins; I would suggest to my fellow-engineers that they make notes on this relation, whenever opportunities present themselves. It may be said that this is not likely to have much practical value, since the depth from which the ore may be profitably extracted is likely to be much less than the deduced depth of the fissure. The question has a bearing, however, upon that of the source from which the ore was derived; and any fact that contributes to a more accurate knowledge of the origin and manner of formation of ore-deposits has practical value, since it enables the mining engineer to make a more accurate forecast of the probable form and extent of any individual deposit beyond the limits of exploration.

4. In regard to the direction from which the ore-bearing solutions reach the *locus* of the deposits, the brief statement made in my abstract that "they came from above," should perhaps have been accompanied by some qualifying explanation. In making the statement, I had in mind the common explanation offered in regard to ore-deposits, that "they came from below," a statement which is more readily made by those who have *not* examined the deposits of which they speak or write, than by those who have, since they are not under the necessity of explaining observed facts in accordance with this hypothesis. The prevalence of this theoretical method of explaining the formation of any ore-deposit is due probably to the great plau-

sibility of the theory generally advanced for the formation of fissure-veins—namely, that the metallic contents of the solutions were taken up by waters under conditions of great heat and pressure (therefore, probably at great depths), and that as these solutions approached the surface, with consequent decrease of heat and pressure, the solvent power of the water decreased also, and their metallic contents were gradually deposited all along the walls of the channel through which they were ascending. No exception can be taken to this theory, as a theory; but before accepting it as of universal application, it is important to see whether it accords with observed facts; and, as Leadville presented a case where it unquestionably did *not* so accord, I made the statement as concise and as strong as possible, to counteract the effect of the "coming-from-below" explanation which would undoubtedly be offered.

Such a one is that made by J. Alden Smith,[11] which has also been quoted by J. Arthur Phillips in his *Treatise on Ore-Deposits*, "that the ore-deposits of this district came from below through fissures originating in the granitic rocks, and extending upwards penetrated the limestones and quartzites to the contact with the overlying porphyry; that these fissures lead to many bedded veins in the limestone and quartzite, and to contact-veins of more or less value between the formations last mentioned, and between those and the granitic formation; and that these fissures and deposits will be extensively and profitably worked for centuries after the contact-deposits now operated are exhausted."

A statement like the above, coming from one whose views would be accepted as of scientific value, might cause much useless expenditure of money in prospecting before it was discovered that the essential facts, upon which it would appear to be founded, existed only in the imagination of the writer. In Leadville, no ore-bearing fissures extending downward from the deposits have yet been found. The facts observed during my examination, and by those who have studied the region since, show that the solutions must have penetrated the limestone from its contact with the porphyry, which is generally its upper surface, and, therefore, downward. An apparent excep-

[11] *Report on the Resources of Colorado*, p. 64 (1883).

tion to this state of things is found, as pointed out by Charles M. Rolker,[12] on Fryer hill, where, according to him, unreplaced dolomite sand forms the roof of the deposit over large areas, and is not found under it. I am ready to admit, for the sake of argument, the truth of this statement for the upper part of the Blue limestone or ore-horizon, which is included in, or both overlain and underlain by, porphyry. The lower sheet of Blue limestone, however, which has porphyry on its upper surface alone, is, as far as observed, replaced only on that upper surface. The exception is, however, in this case only apparent, and does not militate against my supposition. According to this, the intrusion of the porphyry bodies opened channels along, and in some cases across, the sedimentary beds; moreover, observation shows that these porphyry bodies admit the percolation of water freely in every direction through their mass, whereas the limestones are comparatively impermeable except along joint- or fracture-planes. Thus, the contact between porphyry and limestone would, everywhere, be a principal water-channel; and this, in the greater part of the region, is at the lower surface of the former and the upper surface of the latter; but where, as on Fryer hill, the limestone is inclosed in porphyry, it might be attacked from either surface. I can offer no direct reason for the irregular way in which comparatively unaltered remnants of dolomite are left on Fryer hill; but it seems no more abnormal than the irregular distribution of the rich ore within the mass of vein-material, or the fact that, in some places, there is no ore at all at the contact. I cannot quite agree, however, with Mr. Rolker's opinion as to the persistence of the dolomite sand in the roof of the ore-body. His observations in the Chrysolite ground would naturally have been more thorough than mine; but, if my memory does not deceive me, unreplaced dolomite occurs there under, as well as over, the ore-body, as it certainly does in the Little Chief, Virginius, and other claims. It is to be remarked further that, as the rich ore-bodies are found mostly in the upper part of the ore-horizon, the upper surface has been far more thoroughly explored than the lower, and much unreplaced limestone may exist at this lower surface which has not yet been found.

[12] Notes on the Leadville Ore-Deposits, *Trans.*, xv., 273 (1886–87).

It is hardly possible to establish *a priori* any general direction for the flow of underground waters at considerable depths below the earth's surface. In the distinctly stratified rocks, which form the immediate surface, and in which they may flow with comparative freedom, they obey, within certain limits, the laws of hydrostatic pressure; but, at the great depths at which the Leadville deposits were formed, their flow must have been very slow,—a percolation or mere capillary circulation, for the most part. It may be assumed, in general, that cold waters would have a general downward tendency under the influence of gravity, while superheated waters would under certain conditions be forced upward; but the movement would not necessarily be vertical in either direction at any given point. In the present state of geological science, it is not possible to predicate for any given point within the earth's crust that the flow of underground waters *must* be either upward, downward, or sideways. There is an *a priori* possibility of either direction; and the most probable one in any particular region must be determined by an actual study of the geological conditions at that point. For this reason, it seems to me, the student of ore-deposits should divest himself as soon as possible of any preconceived bias in favor of the old schools of ascensionists, descensionists, or lateral secretionists, as the true theory, when arrived at by actual investigation, will probably not correspond exactly to the theoretical views of either school, and the time given to arguments in favor of the exclusive correctness of one over the other is more or less wasted.

In his admirably written paper on The Genesis of Metalliferous Veins,[13] Prof. Joseph LeConte, after combating the lateral-secretion views of Dr. F. Sandberger, says that the latter's idea of the ascensionists' theory is a misconception, adding; "Now, I am sure that no one, in this country at least, holds to any such view. All speculators on this subject, I think, now hold that the mineral contents of veins are wholly derived by leaching from the rocks forming the fissure-walls. The ascension theory (if we use that name at all) as properly understood, *i.e.*, the theory which connects vein-formation with solfataric action, is wholly a levigation theory. According to this theory, as I

[13] *American Journal of Science*, Third Series, vol. xxvi., No. 151, pp. 1 to 19 (July, 1883).

understand it, the vein-matters, including the metallic ores, are not derived from an unknown mysterious region of volcanic fires, but are gathered by leaching from the whole wall-rock from top to bottom of the fissure, but mainly from the deeper parts; because these are under heavy pressure and superheated. Subterranean waters, gathering soluble matter from wide areas and great thicknesses of rock, find their way into fissures, and these then become the natural channel back to the surface from which they came." With these views of Dr. Le Conte, as with the rest of his article, I agree in most respects, while differing with him as to their application, and as to some of his geological facts and reasonings, as will be seen later.

The direction taken by the ore-currents in any given case in bringing the material of ore-deposits to their present position could be readily determined, if the source were known from which these materials were derived. Perhaps even less than the direction of the currents is this source susceptible of direct and positive proof; but its probable location may be established by inductive reasoning, and indirect or even negative evidence may be furnished by actual demonstration, which may in time raise this probability very nearly to practical certainty.

5. I stated in the abstract of my report on Leadville that the contents of the ore-deposits were derived from the neighboring eruptive rocks. By "neighboring eruptive rocks," I do not mean that they must necessarily be in actual contact with the ore-bodies; they may be at some distance from the bodies, provided there is no impassable barrier to prevent the passage of solutions from one to the other. From a theoretical point of view, it is evident that the absolute distance is not essential, since all theories of derivation of the contents of ore-deposits involve a greater relative distance of the source, than that which would derive them from the bodies of rock in the vicinity, even if not at absolute contact. Le Conte's ascension theory, quoted above, supposes vein-materials to have been derived from the rocks adjoining the fissure at some indefinite depth, where pressure and heat were abundant. These were present here: the pressure, that of 10,000 ft. of superincumbent strata; the heat, that of immense bodies of slowly-cooling eruptive rock; only the fissure, which his theory conceives, was wanting.

Something analogous to this fissure might be conceived, if

the Blue limestone, which is, in one sense, the matrix of the principal ore-bodies, had occupied a vertical instead of the more nearly horizontal position that it does. At the time the Leadville deposits were originally formed, it was a practically unbroken horizontal bed, more or less replaced by deposits of ore along its upper surface and extending through joint-cracks at varying distances into its mass and in some few cases reaching to its base. If the dynamic action by which the Mosquito range was uplifted, instead of compressing the sedimentary strata and their included eruptive sheets into a series of folds, and fracturing and displacing them by faults, had simply uptilted the whole into a vertical position, we should then have had, in the place of the fissure, a great vertical limestone zone with ore evidently brought in by solutions acting from one side or wall only. It would then seem most natural, in searching for a source from which the metallic contents had been derived, to investigate the rocks on that side. The advantage of the present over such a condition of things is, that the search, instead of being necessarily confined to rocks adjoining a very limited upper portion of the supposed fissure, can be carried on, not only among the various rocks adjoining the whole area of ore-deposition, but for a considerable distance beyond that area.

Search for the source of the vein-materials of the Leadville deposits was carried on by subjecting the various country-rocks to delicate chemical tests, in order to ascertain the presence or absence in them of the most characteristic components of the vein-materials, gold, silver, lead, and baryta. In selecting specimens for testing, those were chosen which came from points so far removed from any known deposit that there could be no suspicion that the materials found might be infiltrations from such deposits. Among the specimens of eruptive rocks, the freshest and least altered were naturally selected, since decomposition might be expected to have acted on such basic constituents first. None of the above substances were found in the specimens of sedimentary rock tested; and the tests of eruptive rock were, therefore, multiplied, as much as the time which could be allotted to their special investigation would permit. The greatest number of tests were those made in the dry way for minute traces of gold and silver, for the reason

that these could be made with far greater rapidity, and consequently in greater number in a given time, than in the wet way. After considerable experiment with methods and materials, it was found possible to determine in this way with accuracy 0.005 oz. per ton, or 0.000017 per cent., of silver, an amount which it would have required an enormous amount of concentration to detect in the wet way.

The results may be briefly stated as follows: Baryta was found in all four specimens of eruptive rock tested for this substance; lead in 14 out of 17 specimens tested; and silver in 32 out of 42 specimens tested. It is to be remarked that the negative results do not necessarily mean an absence of the substance in question, but only that the amount is less than the process employed could detect; so that where lead is found in a rock it is probable that it contains silver also, but in relatively small amount. As the medium percentage of lead oxide in the above tests is 0.0032, if this lead oxide contained 40 oz. of silver per ton, the percentage of the latter in the rock would be within the limit of accuracy given above for our determination of silver, and could not have been detected by the methods employed. Several hundred assays for silver were made, the results of which correspond in general to those given above, but possible sources of error were found in some, and the 42 represent the residue, which had been confirmed as accurate by repeated tests, after all containing any possible source of error had been eliminated.

It may be said that these results do not necessarily prove that the materials of the Leadville deposits were derived from these eruptive rocks, and not from some unknown bodies of rock still richer in these materials at unknown depths. Absolute proof, as I have already said, could not be expected, especially as against an unknown quantity whose resources, being unknown, are in one sense unlimited, but this evidence shows a possibility which, combined with all the other facts that bear on this question in this particular district, amounts to a very strong probability. The quantities of vein-constituents found, though minute, are quite sufficient when one realizes what vast bodies of eruptive rock still exist there, and reflects, moreover, that probably a very much larger amount was present when the deposits were formed, but has since been removed

by erosion. As against the probability that the materials were derived from eruptive rocks below, there is the evidence afforded by the geological structure of the region that the greater mass of eruptive bodies coming under observation are above the Blue limestone, which is only 400 ft. above the Archæan, and that these eruptive rocks came up through the Archæan in extremely narrow channels or dikes, and only spread out in large bodies after reaching the sedimentary strata above; therefore, that in all probability there are no large bodies of eruptive rock beneath, until the far-distant sources of these rocks are reached; further, that the Archæan rocks, as far as tested, were not found to contain these substances.

The criticisms that have been made upon this part of my conclusions are mostly general rather than special. Mr. Rolker maintains that the overlying White porphyry (felsite) should be stained by basic sulphate of iron, if the vein-materials had been derived from it, and says, "against Mr. Emmons's analysis of the felsite stand other analyses which did not find any lead or silver in it (L. D. Ricketts)." To this I answer, the extraction of such minute traces of metallic minerals by percolating waters would not necessarily leave any staining visible to the naked eye, since the minerals themselves are rarely visible, even under the microscope. Moreover, I do not maintain that they came from the White porphyry alone—there are other bodies of porphyry from which they could have been derived; and this porphyry is so universally decomposed, as shown by microscopic examination, that it is difficult to see what all of its original constituents were. Out of 11 specimens of it, included in the above-quoted tests, only three yielded silver, a far smaller proportion than that of the other varieties of eruptive rock, which were, as a rule, less decomposed. Still, as Mr. Rolker himself suggests, this may merely prove that its metallic contents had been leached out. As for the counterproof of other analyses, Mr. Ricketts himself says explicitly,[14] that he made no study of the question of the source of the material, and the fact that his single analysis of White porphyry gives no lead or silver may simply prove that he did not make the special test for these materials on the large amount of rock

[14] *The Ores of Leadville*, p. 46 (1883).

which is necessary in order to detect them. He adds that his analysis "showed scarcely a trace of sulphur, though the rock at one time certainly contained much iron pyrites."

Dr. Newberry's criticisms on my conclusions are entirely vitiated by his complete misapprehension of my views. He assumes that I would derive the ores from superficial igneous rocks, through the agency of surface-waters; but since I myself do not believe that they could have been formed either by surface-waters or from recent or superficial igneous rocks, it would seem unnecessary to refer to his objections to that view in the special case of Leadville. I will merely say that the theory which he proposes as a substitute for mine, "that the plane of contact between the limestone and porphyry has been the conduit through which heated mineral solutions coming from deep-seated and remote sources have flowed, removing something from both the overlying and underlying strata," etc.,[15] is one which he himself would probably reject, if he had had as good an opportunity of examining the geological structure of the region and the relation of the ore-bodies to the surrounding rocks as I have had.

It may not be amiss to call attention to the fact that Professor Newberry has similarly misapprehended Mr. Becker's views as to the genesis of the ores of the Comstock lode. To him Professor Newberry attributes the hypothesis that the Comstock ores were leached from the hanging-wall by cold surface-waters. Becker's memoir contains no such statement. On the contrary, he maintains at length that the ore was extracted from the hanging-wall by *rising* waters of very high temperature, and charged with solvents, acting at considerable pressures.

As regards the general derivation of the vein-materials from eruptive rocks, it will perhaps be wise to state explicitly what I do think at the present time, reserving the right to modify my views if I see fit, as I gain a wider and more exact knowledge of the ore-deposits of the world. I consider that at the present time neither I nor any one else is in possession of accurate geological knowledge of a sufficiently large number of ore-deposits to justify the formulation of that knowledge

[15] *School of Mines Quarterly*, vol. v., No. 4, p. 341 (May, 1884).

into a universally applicable theory of the formation of ore-deposits. Ore-deposits occur in nature under such varied conditions, moreover, that it seems doubtful if any one theory of their formation will be found applicable to all of them, and probably the final theory will be an alternative one. As one of these alternatives, the derivation from bodies of eruptive rock in the vicinity of the deposits seems to have in its favor more evidence, both direct and indirect, than any other now offered.

As indirect evidence, European geologists have long remarked that regions rich in ore-deposits have, in the majority of cases, been regions of long-continued eruptive activity. This association, or coincidence, if such it may be considered, is still more striking in this country; but it is to be remarked that it is with the older and generally intrusive rocks of eruptive origin that valuable ore-deposits are most frequently associated, while they are rare when these rocks only form surface-flows or are outpourings of actual volcanic vents.[16] Newberry[17] brings forward the latter fact as argument against the derivation of vein-materials from *superficial* igneous rocks, and as such it is certainly valid; but the greater part of our ore-deposits are evidently of deep-seated and not of superficial formation. I have no evidence to prove whether recent lavas are poorer in vein-materials than the older intrusive rocks or not; nor is that an essential point, since it is evident that they have been subjected to the leaching process for but a comparatively short time; that the surface-waters which reach them have neither the heat, pressure, nor chemical solvents that render the action of deep-seated waters more energetic, and therefore that concentrations of vein-materials in ore-deposits from them could not be expected to be as frequent or as considerable as those in the older and deep-seated rocks.

Professor Newberry is inclined to doubt the frequency of the association of eruptive rocks and ore-deposits, and says in regard to the mineral belt of the Far West, "the great majority of veins are not in immediate contact with trap rocks, and they could not therefore have furnished the ores." As to the *im-*

[16] *Tenth Census*, vol. xiii., p. 63 (1880).

[17] The Deposition of Ores, *School of Mines Quarterly*, vol. v., No. 4 (May, 1884).

mediate contact of trap rock with these veins, I do not feel that I have sufficient data to contradict his statement, although I am equally confident that it is not justified by accurate statistical knowledge on his part. But the statement is liable to mislead, in that the reader might be led to infer that, in the instances he gives, eruptive rocks do not occur in the vicinity of the deposits, whereas I am qualified, from my own observation and from knowledge gained during my investigations under the Tenth Census, to state that this inference would be diametrically opposed to the facts. Not only are there, in each of the 11 districts he mentions, known developments of eruptive rock in the vicinity of the deposits, but in seven of these districts there are important mines—some of which he has quoted by name in his list—in which eruptive rocks form one or both walls of the deposits.

Professor Le Conte, on the other hand, not only admits the frequency of the association of great eruptive activity with ore-deposition, but also the possible derivation of the vein-materials from eruptive rocks. His view on this subject, which resembles the Scotch verdict "not proven," is, "not that igneous rocks alone supply the materials, but rather that igneous action supplies the heat necessary for solution." He afterwards admits that heat is *not* in all cases necessary for solution. As Professor Le Conte's views may be taken as a fair representation of the best speculative theories on the subject of ore-deposition at the present day, it may be assumed that there are no good *a priori* grounds against the derivation of vein-materials from eruptive rocks; and it remains to consider what direct evidence there is in its favor. Before doing this, I wish to advert to a geological question, as regards which I do not agree with Le Conte's implied ideas. He says: "We never see any stratified rock that has not been igneous rock nor, I believe, any igneous rock that has not become so by refusion of stratified rocks." This statement might be admitted as applied to the earlier stages of the earth's history when its first crust was forming, and yet doubted in such a practical application to the sedimentary rocks now found on the surface, as is made by Professor Newberry when he says:[18] "All the knowledge we

[18] Deposition of Ores, p. 337.

have of the subject justifies the inference that most of the igneous rocks which have been poured out in our Western Territories are but fused conditions of sediments which form the substructure of that country, . . . and it is possible and even probable that the rocks composing the volcanic ridges are but phases of the same materials that form the sedimentary chains."

The estimated aggregate thickness of sediments above the Archæan varies, roughly stated, from 60,000 to 100,000 ft., but, owing to frequent elevations and subsidences, the series is probably never found complete at any one point, and it may reasonably be doubted if the thickness of sediments accumulated at one time and place over the Archæan ever reached even the lowest of the above figures. But, by the agencies of dynamic action and erosion, geologists have been enabled to study not only these great thicknesses of overlying sediments, but great, though unknown, thicknesses of the Archæan formations beneath; yet, nowhere in the vast portions of the earth's crust that have already been examined has any evidence of the fusion of sedimentary rocks into an igneous magma been found. For this reason it seems to me, and I believe I express the sentiments of the majority of geologists who have made a study of eruptive phenomena, that Professor Newberry's inference is not justified by the knowledge we at present possess, and that the region of fusion whence igneous rocks may be supposed to be derived, must be relegated to greater depths, and beyond the reach of the actual sediments which we can now observe on the surface.

The theory that vein-materials have been derived from adjoining rocks is by no means a new one. Both Breithaupt and Cotta admitted the probability of such derivation, provided only the existence of the vein-materials could be proved, while Bischof not only strongly upheld the theory, but by chemical investigation actually detected the earthy or gangue-material of veins in the neighboring country-rocks. Acting on Bischof's suggestion, and employing methods which enabled him to detect minute traces of material in the separate constituents of rocks, Sandberger has been investigating for many years past the country-rocks of European mining-districts. He finds that the basic silicates of the crystalline country-rocks (metamor-

phic or eruptive) contain the same metals as are found in the neighboring deposits, and hence concludes that the materials of the latter were derived from the former.[19] The investigations of country-rocks, carried on by Mr. Becker and myself at Washoe and Leadville respectively, were in the same line of research, although when they were undertaken we had not the advantage of Sandberger's experience, and our methods differed somewhat from his, owing to the peculiar circumstances under which each inquiry was conducted. Our results in either case showed at least a possibility of the derivation of the materials from the eruptive country-rocks, which the geological conditions heightened to a probability. Since that time, I have carried on similar investigations, with some improvements in methods suggested by experience, on the country-rocks of other districts, notably those of Ten-Mile and Silver Cliff, Colo., which have been in the main confirmatory of those obtained at Leadville. Although the work thus far done in this line covers but a small portion of the field of investigation, it affords valuable indications from which one necessarily draws conclusions, and which certainly point a way for further research that promises to be fruitful in results. The conclusions that I have reached thus far are, that the vein-materials are probably derived from country-rocks in the neighborhood of the deposits, though they are not necessarily in absolute contact, and it may even happen that they cannot be seen at the surface. And the chemical tests thus far made show that the eruptive rocks rather than the sedimentary are the more likely to carry the materials from which the vein-materials have been derived. I am by no means prepared to say that eruptive rocks will everywhere be found to be the source of the vein-materials; indeed, it would seem that there are many deposits where this would be impossible; and yet it often happens that the published descriptions of such deposits are not sufficiently complete or exact to enable us to form a decided opinion one way or the other.

Professor Newberry considers[20] that an unanswerable argument against the theory of lateral secretion is furnished by the great diversity of character exhibited by different sets of fis-

[19] *Untersuchungen über Erzgänge* (1882).

[20] *School of Mines Quarterly*, vol. v., No. 4, p. 334 (May, 1884).

sure-veins which cut the same country-rock. It seems to me that a certain amount of diversity might be allowed in different sets of veins in the same belt of rock, without disproving the theory as I understand it; first, because the derivation is not confined to the immediate wall-rock; secondly, because observation shows that such accessory or accidental constituents as these vein-materials may vary very greatly in the same body of rock; and thirdly, because the determining cause of precipitation or deposition might differ in the different sets of fissures, so as to produce a difference in the character of deposition from one and the same solution. Dr. Newberry does not state directly how great a diversity he considers necessary to prove his argument; but the only instance in which he actually cites the character of the ores has been unfortunately chosen for this purpose. It is that of the Humboldt, the Bassick, and the Bull-Domingo mines, near Rosita and Silver Cliff, which, he says, "are veins contained in the same sheet of eruptive rock, but the ores are as different as possible." In point of fact, the Bull-Domingo deposit occurs in Archæan gneiss, while the Bassick and Humboldt bodies are in separate and distinct bodies of andesite, evidently belonging to different outflows.

To summarize the above somewhat discursive remarks: The present tendency of the results reached by careful and well-authenticated determinations of the origin and manner of formation of ore-deposits is in favor of a continually increasing applicability of the following conditions:

That they are deposited from solutions made by percolating waters.

That the deposition takes place very rarely in actually open cavities, but most frequently by a metasomatic interchange, or by replacement of the more soluble or more accessible portions of a rock or members of a rock-series.

That these solutions do not necessarily come directly upward, but simply follow the easiest channels of approach.

That these materials are not immediately derived from sources at some unknown depth, but from neighboring bodies of rock within limited and conceivable distances.

That where, as is so often the case, ore-deposits are associated with, or in the vicinity of, bodies of eruptive rock, especially

the older intrusive rocks, there is a reasonable probability that their materials have been derived from these rocks.

In order to accumulate facts upon which to form any well-grounded, broad generalization upon these very important subjects, we need, on the part of mining engineers, an almost indefinite multiplication of such papers as those of Messrs. Ricketts, Freeland, and Rolker on the Leadville mines, giving facts in the minute detail which can only be arrived at by long personal observation and study. Such papers should, as far as possible, be based upon authoritative determinations of geological structure of the region where the mines occur, and such determinations it seems to be the proper province of a governmental geological survey to furnish, as private individuals cannot be expected to have the extended field-experience, or to be able to carry out the costly investigations which they necessarily involve.

No. 2.

Structural Relations of Ore-Deposits.

BY S. F. EMMONS, WASHINGTON, D. C.

(Boston Meeting, February, 1888. *Trans.*, xvi., 804.)

"The obscurity which still veils from us the true nature of veins will become more and more cleared up when they can be considered in connection with the geological structure of the regions in which they occur." [1]

THESE words, according to Lossen, the biographer of the late Dr. A. von Groddeck, of Clausthal, were the last received by him from that eminent man, perhaps the most far-sighted and carefully progressive of recent writers on ore-deposits. They seem to me to form a fitting text for what I am about to say; since I find that many of the conclusions at which I have arrived by my own study of the structural relations of ore-deposits, or, in other words, of the structural and dynamic geology of the regions in which they occur in this country, have been similarly determined by him within recent years in Europe, and especially in his home field of work, the Harz.

I shall not enter upon a detailed account of how far other workers may have arrived at similar conclusions with myself, since these questions of priority are of little interest, except to those immediately concerned; but will briefly present the methods by which, in my work in this country, I have arrived at certain generalizations, and will point out the practical bearing which they may have upon the work of mining engineers.

In my first thorough and systematic examination of an important group of ore-deposits, viz., that of Leadville, Colo., I was enabled, through the generous facilities afforded me by the then Director of the Geological Survey, Clarence King, to

[1] "Das Dunkel, welches uns die wahre Natur der Gänge noch immer verhüllt, wird sich mehr und mehr lichten wenn sie im Zusammenhang mit dem geognostischen Bau der Gegenden, in denen sie auftreten, betrachtet werden können."

make a most elaborate and detailed study of the geology, not only of the immediate vicinity of the mines, but of the adjacent mountain regions, based upon accurate topographical and underground maps, and thereby to determine the structural relations of these ore-bodies with an exceptional degree of detail and accuracy. The inductions based upon these structural relations have now borne the test of seven years of active exploration by a most energetic and enterprising mining community, and their substantial accuracy has been so abundantly proved as to afford an excellent practical illustration of the importance, in this class of deposits, of the structural study.

In entering upon this work, I was, I must admit, far from familiar with all that had been written upon the theory of ore-deposits, and I purposely refrained from reading up upon the subject until my field-work was completed, in order to avoid the danger of any unconscious bias which might influence my interpretation of the facts of nature. It was commonly said at that time of the Leadville deposits "that they went contrary to all the theories of geologists." Such statements are in general, I find, liable to originate in a misapprehension, either of the true conditions which prevail at the locality in question, or of what are the best geological theories. In this case I found, in two respects at least, that the process of ore-deposition at Leadville was not in accordance with the most widely accepted theories upon the subject. First, they were not the filling of pre-existing open cavities or caves in the limestone, but had been formed by a gradual replacement of the rock-material by the substances brought in by the ore-bearing solutions. Secondly, these solutions did not come directly from below, as seemed to be considered a necessary condition for the deposition of ores, but in this case could be proved to have reached the immediate *locus* of deposit from above.

As I pointed out in a paper read before the Institute two years since,[2] in stating the results I had arrived at in regard to the genesis of the Leadville deposits, I made no claim of presenting any complete general theory or classification of ore-deposits at that time, nor have my observations been sufficiently wide to enable me to do so now. I did, however, con-

[2] This volume, pp. 1 to 25; *Trans.*, xv., 125 (1886–87).

clude, as a result of my investigations, that existing theories and classifications were inadequate to account for the various forms under which ores are found in nature, and that this inadequacy arose probably from the want of some common underlying genetic basis. Far too few of the descriptions of ore-deposits in various parts of the world, upon which the existing theories have been founded, are based upon accurate determinations of their structural relations. I have, therefore, been emboldened to assume that, by giving more attention to these structural relations than has hitherto been done, many existing uncertainties might be cleared up, and perhaps, in time, a rational or natural classification of ore-deposits might be formed. In the paper above mentioned I stated the conclusions I had been enabled to form from my Leadville and later studies in regard to the genesis of certain ore-deposits, mainly those in limestone, and touched lightly on their probable application to what are known as fissure-veins, of which I had, up to that time, had but limited opportunities of personal observation. Since then, however, especially during the past summer, I have visited many so-called fissure-deposits of great variety of type, and during these visits I have been so struck with the uniform occurrence of certain elementary structural conditions that I have ventured to make some preliminary generalizations based upon them, that seem likely to find a very wide practical application, and to furnish a basis, with modifications that may be afterwards introduced as a result of wider observation, for a general classification of ore-deposits. Whether this prove to be the case or not, it seems that this method of regarding ore-deposits, while I can hardly claim for it much that is absolutely new, has the merit of being a simple, rational method, which obviates many of the uncertainties and misapprehensions, especially in practical application, that constantly arise from the more complicated existing systems.

Preliminary Statements.—The ore-deposits which I propose to consider are original or primary deposits that have been formed later than the inclosing rock. They exclude, therefore, secondary deposits, whether of mechanical or detrital origin, like placers, or of chemical origin, like bog iron-ores, which result from the superficial leaching of other deposits. They also exclude deposits, such as beds of coal, gypsum, and the like,

which have been deposited, so to speak, contemporaneously with the inclosing rock.

Even with these exclusions they include practically all the workable primary deposits of useful metals; for I have yet to see such deposits which can be proved to have been formed contemporaneously with the inclosing rocks. It is possible that in some cases, as Irving holds with regard to the Lake Superior iron-deposits, there was an original nucleus of ore contemporaneously precipitated with the sediments which formed the rocks, but which has been added to to such an extent by percolating solutions replacing the adjoining portions of the inclosing rocks, that the present ore-body is practically a later-formed deposit.

I believe, with Pumpelly, Posepný, and others, that all our workable deposits of the useful metals are the result of a process or series of processes of concentration or aggregation of material previously disseminated in a minute form through the mass of the rocky crust of the earth.

With regard to these deposits there are certain elementary postulates, which at the risk of apparent unnecessary repetition from former papers I think it best to briefly enumerate.

1. That these deposits were formed from aqueous solutions. In other words, they have been gathered up by waters containing varying substances in solution, and percolating through the earth's crust, and again deposited in their present concentrated form under a change of conditions which favored precipitation rather than solution.

It seems hardly necessary at the present day to bring forward any arguments in favor of the aqueous deposition of ores as opposed to the notion of an eruptive origin, which at the best has been a theoretical view not founded upon carefully and critically determined facts; but if there exist any lingering doubts in any mind as to the capability of solutions to take up and redeposit the various minerals found in our ore-deposits I would recommend a perusal of Daubrée's recent voluminous work upon subterranean waters.[3]

2. That, under given conditions of heat and pressure, all substances are more or less permeable to water. Hence we are

[3] *Les eaux souterraines à l'époque actuelle et aux époques anciennes* (1887).

justified in assuming that, at sufficient depths within the earth's crust, waters circulate through or permeate all rocks, even those apparently impermeable, and thus may dissolve out minute quantities of the more readily attackable materials within their mass, and remove them to some other place. It is evident, however, that these waters will constantly tend to concentrate in such portions of the rocky mass as offer a more ready passage or flow, and that during such passage or flow they will seek relief from heat or pressure, and hence come into differing conditions which may favor precipitation, deposition, or chemical interchange of the materials they carry in solution.

Among the determining causes of solution and of precipitation or deposition, the chemical forces undoubtedly play an important part. The capacities of various alkaline solutions to take up metallic minerals, especially when hot, and the conditions of diminished heat and pressure, or of dilution, which would favor precipitation of these minerals, present an extremely interesting and important subject of discussion; but it is one that would take too much time to treat within the limits of this paper. I shall, therefore, confine myself as far as possible to the mechanical or structural conditions which would favor ore-deposition; in other words, consider what are the natural water-channels within the earth's crust, and what forms of ore-deposits such water-channels will give rise to, when the chemical and other conditions are such as to favor a deposition of valuable minerals in workable quantity by them.

3. A further postulate, which I insist on the more strenuously for the reason that in former times the opposite view has been so almost universally held among writers on ore-deposits, is that a large pre-existing open cavity is not a necessary condition for ore-deposition. In other words, that ore-deposits are to a large extent the actual replacement of the country-rock by vein-materials, and that the filling-up by these materials is rather that of interstitial spaces than of what might properly be considered open cavities. I by no means deny that a certain limited amount of unoccupied space may have existed in the water-channel previous to the ore-deposition, but I wish to remove the tendency to misapprehension caused by the previously-conceived view, under which, for instance, one might

regard the whole width of an 8-ft. vein as material brought in from a foreign source, when in point of fact more than 7 ft. of it might be more or less completely altered or replaced country-rock, and less than a foot (and this not in one body) represent spaces actually filled in. I can even conceive of cases of veins showing what is supposed to be the comb-structure, from which the idea of the pre-existing open space was originally derived, where this structure is produced by sheeting of the country-rock, the different sheets being replaced by different mineral combinations, as will be explained later on.

Let us consider, then, what would be the natural and most readily available channels which would tend to collect the waters circulating within the earth's crust, and constitute their primary water-courses.

It is evident that the nearest analogy to the flow of underground waters which can actually come under our observation will be found in the flow of springs, especially thermal springs. A study of the phenomena connected with spring-action and deposition, such as has been made by Daubrée in his valuable work above cited, materially aids our conceptions of what may have taken place in the deeper-seated channels which have been in former geological periods the scene of ore-deposition.

One must beware of following this analogy blindly, however, and bear in mind that most ore-deposits must have been formed at considerable depths below the surface, and brought to the comparatively short distance from that surface which they now occupy by upheaval and erosion.

An instance of the errors into which one may be otherwise led is afforded by a paper read before the Institute two years since by Prof. T. B. Comstock,[4] on The Geology and Vein-Structure of Southwestern Colorado.

Owing to the vagueness of Mr. Comstock's statements, and his many misconceptions of geological facts, we cannot always be sure of his meaning; but from a careful consideration of this paper I infer that he considers the head of Red Mountain creek in that region, which he calls a crater-like depression, to be an extinct geyser-basin, and that the ore-deposits opened by the mines now worked there have been formed by geysers.

[4] *Trans.*, xv., 218 to 265 (1886–87).

Now a geyser, as its name implies, is a spring which violently ejects its waters into the atmosphere, and hence, even more than other springs, is essentially a surface-phenomenon.

As, since the ore-deposits of Red Mountain basin were formed, something like 2,000 ft. in thickness of rock-material has been eroded away to form the basin, it is evident that they could not have been formed by a geyser, nor can it be determined at the present day whether geysers ever existed there or not. Apparently Professor Comstock has thought to find a resemblance between certain rounded ridges of light-colored rock near these mines and the mounds formed by deposits from the springs in the Yellowstone Park. Instead, however, of being surface-deposits, they are simply portions of the andesitic country-rock from which acid waters have removed the basic constituents, perhaps depositing a certain amount of silica in their place; the resulting quartzose masses, offering greater resistance to the disintegrating effect of atmospheric agents and to erosion than the surrounding rocks, have been left as mound-like ridges protruding above the general surface, more or less independent of the natural drainage-channels.

There are abundant mounds formed by deposits from springs in the vicinity of Red mountain, but they consist mainly of bog iron, and are formed by oxidizing surface-waters passing through and decomposing bodies of sulphides of the metals, whose action is quite distinct from, and in some sense the reverse of, those which originally formed these bodies. It would seem almost unnecessary to insist on this distinction, but I recall the description given me of similar deposits in the Redwell basin in the Gunnison region by J. K. Hallowell, who claimed as exact a knowledge of the geology of that district as Professor Comstock does of the San Juan region. According to him, galena and pyrite can be found in actual process of formation there at the present day. On personal examination, I found that a bog iron-deposit had been formed throughout the débris filling the bottom of this ancient glacier-basin, and in one place rested directly on the outcrop of a vein carrying pyrite, galena and other sulphurets. Owing to the extremely decomposed condition of the country-rock of this vein where the bog iron rested on it, Mr. Hallowell had evidently concluded that it formed part of the spring-deposit, failing to

recognize the dividing-line between recent deposit and original, though decomposed, rock-formation.

Although, in studying a given deposit, it is not safe to assume that there has been a spring at that particular spot, from whose waters it was deposited, it is evident that the underground flow of waters which formed ore-deposits would have followed similar laws to those which regulate the flow of water now appearing at the surface as springs.

Natural Water-Channels.—From the study of the flow of spring-water, three principal structural conditions may be conceived which would produce natural water-passages in the rocks which form the earth's crust:

1. Sedimentation or bedding.
2. Intrusion of eruptive masses.
3. Dynamic movements producing fractures across rock-masses of differing origin or composition.

1. From the first of the above causes, by the deposition of alternating strata of varying degrees of permeability, or by successive flows of igneous rocks, natural channels will be afforded parallel to the stratification or bedding-planes, and more or less coincident with them according to the nature of the material of which the bounding beds are formed. This is proved by the fact that where such strata or beds are inclined or plicated, and afterwards eroded so that their edges outcrop, springs will be found along such outcrops where they are at a lower level than the general mass of the strata, or artificial springs may be produced by artesian borings which fulfill the necessary hydrostatic conditions. It is hardly necessary to quote instances of flow of spring-waters under the simple conditions of alternating strata of permeable and impermeable sedimentary rocks. The evidences of water-passage between flows of eruptive rock are well shown in Idaho and eastern Oregon, where whole rivers disappear beneath the great lava-flows that cover such immense areas of surface, and reappear at some lower level at the bounding-plane between the successive flows, evidently having sunk through some natural fracture and followed a more permeable bed of mud or breccia, such as is generally found alternating with the beds of solid lava.

These primary water-channels along bedding-planes may

be interrupted by either of the two other causes mentioned above.

2. Eruptive dikes or cross-cutting intrusive bodies of any form may interpose relatively impermeable masses across their course, or intrusive bodies, running parallel with the bedding, may render the plane of contact a more ready water-passage than it otherwise would have been. Thus in regions of eruptive activity, springs, especially thermal springs, are generally found along the outcrop of the contact of the later eruptives with the rocks through which they have passed.

3. The interruptions to these primary water-channels resulting from the varied forms of rock-fracture caused by dynamic movements are so manifold and numerous that it is not always possible to trace back to cause from effect. Frequently springs issue from the outcrops of fault-planes; and, when crossed underground, the latter are generally found to be water-bearing. It is easy to conceive that where a series of beds, including certain permeable or water-bearing strata, are broken or displaced by fault-movements, the current along the permeable strata may be interrupted. On the other hand, the passage of water along this new water-channel may not be continuous to the surface, but may only follow it until it meets another permeable stratum and turn off again along that in a manner similar to the well-known occurrence in artesian wells, where, if the bore-hole be not protected by a water-tight casing, the water rising from some deeper bed may gradually be dissipated in other permeable beds passed through by the drill, between the water-bearing bed and the surface, and the surface-flow be finally lost altogether.

It is evident that the greater number of underground water-channels, though perhaps not those carrying the largest volumes of water, will be afforded by the multitudinous fractures in the crystalline or eruptive rocks and in the older and more metamorphosed sedimentary strata. In one sense these might be made to include the contact-channels along dikes and intrusive bodies of eruptive rock also; for it is probable that such bodies, when forced up from below, have followed some previously-determined fracture or natural division-plane.

Before proceeding to consider how far the origin of various

types of ore-deposits may be ascribed to the passage of mineral-bearing waters along one or more of the above natural water-channels, I will mention another possible class of division-planes in rocks which have been considered by some as the origin of mineral-bearing fissures, but to which, so far as I know, that of springs has never been ascribed. These are contraction-planes or joints. The most evident examples of them are naturally found in eruptive rocks, notably the prismatic joints of more recent eruptives. It is possible that the division-planes which tend to separate most eruptive rocks into parallelopipedic fragments may have been originally determined by contraction of the mass, but it is probable that the actual fracturing along these planes was produced by dynamic movements. Whether sedimentary rocks contract after deposition from the expulsion of the water they must have contained when forming the sea-bottom, may be considered an open question. One thing is evident: that contraction-planes must be confined to one rock-mass or bed, and cannot cross several of them, as do most mineral-bearing fissures. It is also evident that, as contraction-planes alone, there would have been no movement or pressure along them. Hence planes where evidences of movement or pressure are found cannot result from contraction alone. For these reasons, and the further one that I have never yet found ore-bodies deposited on planes which I could feel assured were the result of contraction alone, I think it safe to leave contraction-planes out of consideration for the present, at least.

Ore-Deposits Along Bedding-Planes.—The greater part of our ore-deposits are found in mountainous regions where eruptive and dynamic action has been most energetic; consequently, deposits resulting from the flow of water along bedding-planes alone, unconnected with the other classes of water-channels, form but a small proportion of the whole. There are, moreover, other conditions than the simple readiness of flow of water that come into play. It is apparent that deposition will take place more readily from a comparatively sluggish than from a rapid flow; hence conditions that tend to retard the flow or cause a partial stagnation at a given point will favor precipitation at that point. Such would be the actual contact of an impervious stratum, *e.g.*, a bed of clayey material, with a

readily pervious one like a loose sandstone. Again, in plicated strata, points where by sharp folding the beds are more closely compressed together—as on the side of the fold—than at other points, are often found to carry larger bodies of ore. The chemical composition of the different beds is also a most important factor; so much so that in regions like the Ten-Mile district, where thin beds of limestone are found scattered through considerable thicknesses of sandstone and shales, the ore of the so-called bedded deposit is almost exclusively confined to the more readily attackable limestone. The term "bedded vein" or "deposit," as derived from von Cotta's *Lagergang* (literally, *bed-vein*), might be objected to as seeming to imply that the ore was deposited contemporaneously with the inclosing beds, and for this reason the less concise term, "deposit along bedding-planes," would be preferable. Where the deposit occurs at the junction of two beds of very dissimilar composition, like limestone and quartzite or slate, it is often called a contact-deposit, but it seems that this term should be confined to those of the next class, contact-deposits with rocks not of contemporaneous formation.

Instances of deposits of this class that occur to me are those of the Ten-Mile region, the Red Cliff region, and others in Colorado, which are mostly along the bedding-planes between limestones and argillaceous beds, though at Red Cliff some are found in quartzites. The iron-ore beds in the Silurian rocks of the Appalachians are probably of this class, for Prime reports that he finds evidence that they are the replacement of the limestone rock, hence cannot have been formed, like bog iron-deposits, contemporaneously with the inclosing rocks, as Newberry maintains. They are not necessarily confined to the immediate bedding-plane, but in a porous rock may spread through the mass, like those of Silver Reef, where precipitation has been probably induced by the presence of some reducing-agent of organic origin. The copper-deposits of Mansfeld in the Harz, and the lead-deposits of Commern in the Eifel, may be found to belong to the same class, though they have generally been considered to be of contemporaneous origin with the inclosing Triassic beds.

It will be evident *a priori* that mineral currents following stratification-planes cannot be considered as necessarily coming

from below, as has been assumed by many to be the universal direction of such currents. As I have shown in a former paper,[5] the direction of flow of underground waters cannot be determined beforehand for a given point; as this flow is a circulation, its direction may vary according to the local conditions which would govern it. As far as my observations go, in deposits from currents following stratification-planes the waters have sunk into the bed from its upper surface as if under the influence of gravity.

Deposits Along Contact-Planes.—Mineral-bearing solutions gathering in or flowing along the planes of contact of eruptive bodies with rocks through which they have been forced would have a tendency to deposit their contents along such planes, whatever the direction of their flow. If they were ascending currents, it may be conceived that they were coming from a hotter region, or from the vicinity of a larger and not so thoroughly cooled mass of igneous rock, where their solvent power was greater, to a cooler region, in which this solvent power would be relatively less. If lateral or descending flows, gathering from the mass of one of the walls of the fissure, precipitation might be induced from the solutions thus brought in by a retardation or temporary stagnation of the flow, by dilution through mixing with other waters already circulating in the fissure, or by some chemical interchange resulting from contact with the other wall, if a rock of different chemical composition from that through which the solutions had been passing. For these reasons it seems advisable to distinguish such deposits from those along stratification-planes on the one hand, or along rock-fractures on the other, even in those cases where the contact-plane may be in part, or wholly, coincident with a stratification- or fracture-plane.

It is quite a common practice among miners to designate as "contact-deposits" ore-bodies occurring along the dividing-plane between two bodies or beds of different rocks, even when such plane is simply a stratification-plane. Such practice should in my opinion be avoided, and the term confined to the planes defined above, which are distinctly of later formation than stratification-planes, and in which the conditions of deposition would have certain distinctive characters.

[5] This volume, p. 14; *Trans.*, xv., 137 (1886–87).

Contact-planes as defined above will more frequently be found to coincide or connect with planes of rock-fracture, since one can hardly conceive of sheets of eruptive rock being forced through existing rock-masses in the form in which we now find them, unless they had followed some already-determined line of fracture, or at least of readiness to be forced open, and it is well known that eruptions of lava at the present day are generally preceded by earthquake-shocks, which probably involve a very considerable shattering and fissuring of the earth's crust in the vicinity of the eruption.

Ore-deposits along contact-planes are very common, and mining engineers can doubtless recall frequent instances which have come under their own observation. The famous Leadville deposits are in great part instances of the less common type of deposits, in contact with intrusive bodies which have generally followed stratification-planes. Among them, however, are deposits along the contact of cross-cutting eruptive sheets, the so-called second contacts, and in some instances the ore-currents have followed rock-fractures, and hence belong to the third class. As in all deposits in limestone, owing to the readily attackable character of the rock, the actual form of the various deposits at Leadville is extremely irregular; more so than it would be in a more siliceous rock; but I have as yet been unable to conceive of any classification, founded on the form alone, that would essentially aid in the description of such bodies, or help the miner in exploiting them.

Of deposits along the contacts of dikes or cross-cutting bodies of eruptive rock, hence generally occupying a more nearly vertical position, abundant examples are found throughout the Archæan areas of the Rocky Mountain region, most of which are commonly classed by the miner as fissure-veins, because of the prevailing prejudice in favor of the supposed greater value of that type of deposit. It may be that the whole mass of a narrow dike is impregnated with mineral, and thus constitutes the ore-body; but in the structural sense it is none the less a contact-deposit, since the deposit has been made by waters acting from the contact-planes outward. Instances of such deposits are frequent in Boulder, Gilpin, and Clear Creek counties, in Colorado.

On the other hand, when the deposit occurs along a plane of

contact of two dissimilar bodies of rock brought into juxtaposition by faulting, like the Comstock lode, it would more properly belong to the third class.

Deposits Along Planes of Rock-Fracture or Fissures Produced by Dynamic Movements.—Many somewhat divergent views have been entertained at various times by geologists as to the origin, manner of formation, and even the proper designation of the many kinds of fissures, cracks, and joints that traverse the rock-masses forming the earth's crust. Those that I propose to briefly present here are the ones which a long field-experience has shown to accord best with the facts of nature, and which, as far as my reading has extended, are in essential harmony with those entertained at the present time by the best structural geologists both of this country and of Europe.

The most prominent and readily remarked of these rock-fractures are the great faults which have played so important a part in determining the orographic relief of our globe, a part second in importance only to that of the flexures or plications of the strata, to which, as I shall show, they are closely allied both in origin and manner of formation. The greatest of these faults often extend for miles in length, and the displacement of the opposed rock-masses on either side of the fault may amount to several thousand feet. Minor faults or displacements, which are found in infinite variety, especially in regions of great dynamic disturbance, may not produce any readily apparent effect upon the surface-features, and yet may be recognizable as determining the flow of springs, or be detected by the underground workings of mines. They have been most thoroughly studied in the workings of coal-mines, where the importance of careful underground mapping is most generally appreciated, since the determination of the direction and amount of throw of such faults has an actual money-value. Much has been written about methods of making such determinations, but more attention seems to have been given to reducing them to mathematical formulæ than to tracing their origin or connection with other earth-movements. In all these rock-fractures the evidence of a movement of displacement, as disclosed by the discrepancy or want of correspondence in the adjoining walls, is usually very prominent.

There are other and much more numerous rock-fractures, in

which there is either no movement of displacement, or it is so slight as to be with difficulty detected. Among them certain classes are characterized by their frequency and their general parallelism in two or more co-ordinated directions, and at angles often approaching a right angle with each other. To these, owing to their apparent uniformity of character, the name of joints, or cross-joints (inasmuch as they are apt to cut across the strata), has generally been given by English-speaking geologists.

As regards the designation of these various forms of fissure or rock-fracture, from the very fact that there has been so little agreement as to their genetic relations, there has necessarily been a great want of uniformity in nomenclature. In different countries, and even in different districts in the same country, local terms have been used to describe phenomena supposed to be peculiar to the locality, which have been perpetuated by geologists and have thus introduced into geological literature a greater diversity and variety of terms than is justified from a strictly genetic point of view.

Daubrée, in his comprehensive view of the phenomena attending the flow of underground waters, recognizing the hopelessness of assimilating all these local terms, proposes the general name of *Lithoclases* (rock-fractures) for all rock-fractures of whatever nature, and, as principal subdivisions, uses *Paraclases*, to designate those in which the movement of displacement is readily apparent (in other words, what are generally called faults), and *Diaclases* to designate those that are generally known as joints and in which there is no perceptible movement of displacement, but which are characterized by a parallelism and uniformity of distribution, and traverse different rock-masses. To both of these he attributes a mechanical origin; in other words, considers that they are the result of dynamic movements of the earth's crust. He further designates all the rock-fractures of feeble dimensions, which are confined to a given rock-mass and render it liable to break up into small fragments under various influences, as *Leptoclases* (small fractures), subdividing these further into *Synclases* (contraction-fractures), or those which, like prismatic joints, are produced by the contraction of the rock-mass, and *Piésoclases* (compression-fractures), those small fractures, without any ap-

parent regularity, whose frequent striated surfaces show them to result from a movement of compression like the *diaclases.*

On the other hand, Heim, who is the best representative of the German ideas on structural geology, in his classic work on the mechanism of mountain-building,[6] simply divides the larger rock-fractures into two classes: fold-faults (*Faltenverwerfungen*) and fissure-faults (*Spaltenverwerfungen*), both of which are produced by tangential or lateral compression of the upper portions of the earth's crust. In the former, this pressure has resulted in a general plication of the beds involved, which has progressed to such a point that the limit of their plasticity or capability of bending has been passed, and the tension relieved by actual fracture and displacement. In the latter, the fracture has taken place without any perceptible bending of the rock-masses adjoining the fault, the tension being relieved by sudden shatterings in the nature of earthquake-shocks, or because the lines of fracture were already determined, and the cohesion sufficient to admit of the preliminary plication of the beds no longer existed. He afterwards traces the effects of the same forces upon the internal structure of individual rock-masses, and shows that cleavage- and foliation-planes are, so to speak, diminutive faults, and that the effects of these movements are appreciable even in the microscopic structure of the rocks.

While Daubrée's nomenclature, as such, is the most complete and comprehensive thus far presented, the attempt to introduce into so practical a science as mining geology so many new and strange terms would seem to be of very doubtful advisability. For the present purposes, therefore, it seems sufficient to use the terms "fold-faults," "fissure-faults," and "compression-joints" to designate the most marked types of the various rock-fractures, bearing in mind that, as they are supposed to be the result of the same general force of compression, it may not always be possible to draw a definite line of distinction between the types.

Causes of Fracture.—It seems hardly necessary to state at the present day that the force which produces the folding, faultings, and rock-fractures—in short, the mountain-building force,

[6] *Untersuchungen über den Mechanismus der Gebirgsbildung*, vol. ii., p. 44 (1878).

is to be considered as a result of the secular contraction of the earth's crust. Of late years, however, some theoretical arguments have been presented by physicists tending to throw doubt upon the adequacy of the force which might be produced by secular contraction to account for what they assume to be observed facts. Further, certain American geologists have thought to find conditions which, according to their reading of the facts, contraction could not account for, and for some of which it has even been thought necessary to revive the old and long ago abandoned hypothesis of a vertical upthrust.

As regards the theoretical objections, it may be said that mathematical demonstrations are of questionable value in a science like the geology of the present day, in which the exactly determined facts are as yet too few to afford premises of mathematical exactitude upon which to base them, and that those who are arguing against the contraction theory have presented no adequate hypothesis to take its place.

On the other hand, among practical observers in geology the personal equation forms so large a factor that it may be fairly questioned whether the readiness of the gentlemen referred to above to find facts that could not be accounted for by the contraction theory was not enhanced by a previously-formed opinion of its inadequacy and a desire to see it disproved. In my own pretty large experience in the same general field in which they have worked, I have found that this theory not only accounts for, but is the only one that *will* account for, all the observed facts; and where my observations extended over regions actually mentioned by them, I have found their explanations not to be in accordance with the facts of nature, as I read them.

Under the contraction hypothesis, the forces exerted may be concisely described as resulting from the attempt of an already consolidated crust to fit itself more closely to a shrinking nucleus. Their effect is felt probably only upon a comparatively thin outer portion of the earth's crust: at any rate, it is a very thin portion of this crust which comes under our observation. This crust may be conceived, therefore, as having been since its first formation in a condition of tension, a gradually increasing force which from time to time found its relief in earth-movements producing corrugations on its surface, and

hence relative elevations along certain orographic lines, which from some reason or other were lines of least resistance or of weakness. Such lines, once determined, have been the scene of most marked expression of these constantly-recurring movements of relief from tension. Closely connected with such movements have been the eruptions of igneous material, forced up from below, either from a region of permanent fusion of the material of the earth's crust, as was formerly most generally maintained, or, according to later views, from local reservoirs brought into a fused condition as a more or less direct result of these movements, by the disturbance of equilibrium between the various forces involved in the general condition of tension. Whatever their source, the eruptions of igneous rocks have unquestionably had a very close connection with orographic disturbances, and further, have indirectly played an important part in the formation of most ore-deposits.

Observation teaches us that these successive periods of dynamic disturbance, or of mountain-building, must have been followed by periods of relative quiescence, during which the regions elevated into land-masses were worn down by atmospheric abrasion, and their comminuted débris carried into the adjoining oceans to form a new series of sedimentary beds. Each successive series of dynamic movements would involve not only this newer series, but also the older and already plicated and fractured series of rocks; and thus the structural conditions are found to be the more complicated and more difficult to decipher, the older the rocks in which we have occasion to study them.

The rock-masses of which the earth's crust is formed possess to a certain degree both rigidity and plasticity: the relative degrees of these qualities may vary not only with the composition, association, and molecular structure of the different masses, but, in the same mass, with differing conditions of heat and pressure under which it exists at a given moment. Hence it is impossible to determine *a priori* whether a given amount of compression will produce plication and fracture combined, or fracture alone.

In a general way we know that certain rocks are more plastic than others: for instance, argillaceous rocks more than siliceous rocks; amorphous rocks more than crystalline rocks.

Further, it is evident that under moderate temperatures distinctly stratified rocks will be more readily plicated than massive or crystalline rocks; in other words, under given conditions the latter would be more fractured than the former.

The fracturing of rocks, moreover, takes place the more readily the lighter the load upon them; in other words, plasticity increases with pressure. Thus, at sufficient depths below the surface, or under the weight of a sufficient mass of superincumbent rocks, fracturing of the rock-mass would no longer be possible, and compression would only result in some plastic deformation. Heim places at 15,000 ft. the depth at which all fissures sufficiently open to admit the passage of waters must necessarily cease.

Heim further shows that the plasticity of a given rock-mass will be greater under a slow-working pressure than under a sudden shock, or under the effects of a force of rapidly-developed energy. Now it is a fact of observation that the elevation of mountains, which is in the main the result of plication, is an immensely slow movement, lasting at times through entire geological periods. We can readily conceive, therefore, that while, as observation shows us, under this slow-moving force great thicknesses of beds have been folded together like so many sheets of paper, when the limit of plasticity was reached and fracture took place, that this would be a relatively rapid action, more in the nature of a sudden shock; indeed, that under such enormous pressure as must necessarily exist, the movement past each other of the lips of the fracture, involving hundreds or even thousands of feet of rock-masses, may have produced a series of violent shocks, which propagated themselves through the adjoining rock-masses, and produced in them a series of fractures such as we see in so-called cross-joints. According to the theory that earthquakes are the relief of tension in the earth's crust, this propagation of movement would resemble the vibratory movement observed in modern earthquakes. Such an origin for cross-joints has already been suggested by W. O. Crosby.[7]

It has been objected, however, that while the propagation of such vibratory movements would produce the main parallel

[7] *Proceedings of the Boston Society of Natural History*, vol. xxii., pp. 72 to 85 (1882-83).

joints at right angles to the direction of movement of the wave, it is not so easy to account for the correlated joints which cross the primary joints, generally at a large angle.

If, however, we assume that all the rocks thus fractured were under a tension which, acting more slowly, would have produced folds, and if this tension was not simple, but complex, or acting in more than one direction at the same time, so that not one, but two or more systems of folds would finally be produced; then, by the crossing of these systems of folds, there would result not only a plication along parallel axes, but at the same time a torsion of the beds or rock-masses involved. The assumption of a torsional strain, combined with that tending to produce plication, admits of an almost infinite complexity of rock-fractures as a product of these forces under the various conceivable conditions attending dynamic movements.

The foregoing theoretical consideration of the forces which may have produced the various rock-fractures under consideration has been purposely made very brief, and is hence possibly somewhat incomplete, for the reason that in so practical a science as mining geology, the outward manifestations of geological phenomena—the effects—are, in my opinion, of more importance than the causes, which always remain to a certain extent in the region of hypothetical conjecture, and that if one becomes too much wedded to a certain theory he is in danger of adjusting his facts to that theory.

I shall, therefore, insist more particularly upon the physical phenomena which characterize these rock-fractures, as determined by actual observation, and for which, while the above-mentioned hypotheses seem at present to account for them, I shall be quite ready in the future to adopt any other explanation that, by my own studies or by those of others, may be presented as more reasonable and adequate.

Common Characteristics of Compression-Fractures—There are three phases of structural evidence of rock-fractures and displacement resulting from compression, one or more of which I have found to characterize the various types of fissures carrying ore-deposits, which have come under my observation. These are:

1. Striations and "slickenside"-surfaces.
2. Breccia or fragmentary material in the fissure itself, or

zones of crushed or broken rock-material included between intersecting systems of fissures.

3. A sheeting of the country-rock parallel with the main fracture; in other words, the occurrence of a system of minor fractures which divide the country-rock up into a system of approximately parallel plates or sheets. The distance between these parallel fractures, or the thickness of the sheets, may be reckoned by inches, by feet, or by hundreds of feet, according to the varying texture of the rock-masses involved, or the different dynamic conditions which have produced the fracture.

It will at once suggest itself that these are all phenomena characteristic of faults. But they are also found, at times, where there may be no recognizable evidence of actual displacement of the rock-masses on either side of the fissure or fracture. On the other hand, it will be equally evident that fissures characterized by these phenomena can hardly be the result of contraction, or shrinkage-cracks.

Striations are not confined to well-defined fissures, but are found on smaller planes within rock-masses; but in any case they necessarily seem to give evidence of movement under pressure, be the amount of that movement ever so small.

Fragments of country-rock are often rounded, and writers upon ore-deposits are accustomed to speak of them as having fallen into the fissures from the walls, and, when rounded, as having become so by attrition either against the walls or against each other. As regards the falling in, which seems to imply a fall in a free or open space of considerable dimensions, my observations have led me to consider it of rare occurrence, and to infer that the fragments generally found have been produced rather by the rubbing or dragging of one wall against the other. The greater or lesser size of the fragments would, in a measure, prove a greater or less distance between the walls, but it seems that under the enormous pressure that must have accompanied these rock-fractures, the space between the walls must have been more or less completely filled with attrition-material, only part of which would be actual rock-fragments, and the rest finely-comminuted material, which, under the dissolving agency of percolating waters, would finally result in more or less impure clays. The rounding of the fragments, on the other hand, is readily accounted for as the action of

these same percolating waters, it being a well-recognized fact that the decomposing action of moisture in any form acts more rapidly on the corners or angles of a rock-mass than on its flat surfaces, and the sharper the corner the more rapidly is it eaten away.

Crushed zones are merely larger phases of the same actions as produce the breccia-material, and are subject to the same general laws, only differing in their greater dimensions and the more irregular shape of the inclosing walls.

The sheeting of the country-rock in faulted or fractured regions where ore-deposits abound, is a phenomenon to which hitherto too little attention has been paid. Its importance as a feature of fissure-veins is, however, great both from a geological and from a practical point of view. That it has hitherto escaped due recognition, is probably due to the prevalence of the old idea that vein-deposits are necessarily the filling of open fissures, and to the failure to appreciate to how great an extent they are actually the replacement of rock-material rendered more readily accessible and attackable by the dynamic movements which produced the fissure. This feature will be more fully illustrated in the practical examples given later.

Before proceeding to the consideration of how far these features appear in actual ore-deposits, it will be well to examine the typical manifestations of the above-enumerated rock-fractures where their relations are best shown, independently of whether they may have been mineralized or not.

Typical Rock-Fractures.—The typical form of the *fold-fault*, as observed by Heim in his studies in the Alps, and as shown experimentally by Daubrée in his *Géologie Expérimentale*, may be produced in the following way: If a given series of strata are compressed into a sharp anticlinal fold by longitudinal pressure, the individual strata will tend to expand or swell along the axis, or in the crest of the anticline and in the bottom of the adjoining syncline, while in the intermediate portions—the sides, or as the Germans express it, the shanks (*Schenkeln*) of the fold—they will be contracted and attenuated or drawn out, as it were. When, therefore, the beds in folding have reached their limits of plasticity, the fracturing will take place by preference along the contracted portion; that is, on the sides of the fold rather than along its axis. Such a fault, it is

evident, will be necessarily accompanied by marked plication of the strata on either side. Faults exist in nature, however, in which there is no marked plication of the strata on either side, but which are quite evidently the result of folding, since at one or both ends they pass into an unfractured fold. It is evident, therefore, that the latter type may be undistinguishable from the fissure-fault, in cases where the structure of the adjoining region is so obscured that it is not possible to determine whether the fault actually passes into a fold or not.

Characteristic examples of the above faults occur in the Mosquito range near Leadville, Colo., and will be found illustrated in the maps and sections of the Atlas accompanying Monograph XII. of the U. S. Geological Survey. There the Mosquito fault, which splits into two at its southern end, each branch terminating in a fold, and to the north has been traced for a distance of about 25 miles and may extend as much farther, is a typical illustration of Heim's definition of the fault-fold. Where the adjoining strata are exposed and have not been eroded away, they are seen to be sharply folded and to have once formed part of an S-fold, which has been fractured along one side of the anticlinal axis or on the shank of the fold. The Iron and Carbonate faults, on the other hand, which, though of less extent, it has been possible to study more thoroughly, owing to the many mine-openings along their course, show no evidence of folding in the bending of the strata immediately adjoining them on either side, which are cut across by the fracture nearly at right angles to the bedding-planes throughout the greater part of their extent. They form, however, a definite part of a system of gentle anticlinal and synclinal folds, and pass into an unfractured fold at either end, being, therefore, properly speaking, fold-faults.

In other prominent faults in the district, such as the Ball Mountain, Mike, and Pilot faults, it is not possible to trace their direct connection with folds, and yet it is evident that they were produced by the same general dynamic movements as the others, and form part of the same tendency towards plication, which, in their case, has evidently been counteracted by the greater rigidity of the rock-masses as a whole, resulting from the large proportion of igneous masses entering into their composition.

The phenomena of striation, brecciation, and sheeting of the country-rock are well seen in the Iron and Carbonate faults, which are the only ones that have been explored underground. As I have shown elsewhere,[8] these fault-planes are not mineral-bearing, since the principal mineral deposition in the region was accomplished before the faulting took place. But in cases where the faults cut through ore-bodies, considerable broken and ground-up vein-material has been dragged into the fault-fissure, in quantity sufficient to give rich returns for extraction. The brecciated character of this material is, however, less readily recognized than when the fragments have been cemented together by metallic minerals, as is the case in many fissure-veins. The sheeting of the country-rock in these two faults has apparently been confined to the side of the fault opposite to that from which the pressure came, and has produced what are sometimes called step-faults, the movement of displacement having been partly distributed on several minor planes, a hundred feet or more apart, and parallel to the main fault-plane.

The best region for studying the typical *fissure-fault* that has come under my observation is the southwestern portion of the Elk mountains, in Gunnison county, Colo. This has been a region of intense and repeated dynamic disturbance, accompanied by enormous eruptions of a great quantity of igneous rocks in all the varied forms in which they occur. Elevated glacial amphitheaters or basins, at altitudes of about 11,000 ft., whose walls consist of thinly-stratified and nearly horizontal beds of variegated colors, afford unusually favorable opportunities for tracing the many faults, which form a complicated network over a large area, and for determining the amount of displacement produced by them, which is generally slight and measured by tens or hundreds of feet. Although, as seen on a cliff-face, these faults seem to consist of a single plane of fracture, it is found, when they are examined in underground workings, that what might be called the fissure-plane consists of a series of thin sheets of more or less altered and intensely compressed and striated country-rock, generally only an inch

[8] Notes on Some Colorado Ore-Deposits, *Proceedings of the Colorado Scientific Society*, vol. ii., part ii., p. 85 (Oct., 1886).

or two thick. Where, as is frequently the case, these fissures have been mineralized and constitute important ore-deposits, the original character of the sheets is not readily apparent; but the amount of breccia, consisting ordinarily of small angular fragments of country-rock, cemented by vein-material, sufficiently proves that the fissure is a fault-fissure; and, when explorations on the strike have extended beyond the zone of mineralization, the sheets of country-rock are found to retain enough of the original structure to prove their origin. Further, when cross-cut drifts have been run into the country on either side, a series of more or less parallel cracks or fissures are found, gradually disappearing as the distance from the central fissure increases. As only the ore-bearing portions of such fissures are, as a rule, explored, it is evident that the fracturing and the directions and extent of the fissures can be determined but incompletely. Still, owing to the frequent surface-exposures, a certain regularity of direction is easily detected, showing that the fractures have been determined by definite series of dynamic movements. Although in this particular region the faults are unaccompanied by any considerable plication, yet at no great distance, and nearer a center of disturbance, there has been intense plication, accompanied by fold-faulting.

Similar fissure-faults, with the same phenomena of thin sheeting of the country-rock, and with breccia cemented by vein-material, are found in the San Juan region. Here, also, the directions of the various faults follow certain systems, which a thorough orographic study of the region would, doubtless, enable one to connect with the dynamic movements which produced them.

From these individual fissure-faults there is a gradual transition into the co-ordinated fractures, as a rule greater in number in a given area but of less individual extent, which form a sort of fractured zone with two or more prominent directions of fracture, apparently of nearly contemporaneous formation, which I have called *compression-joints*, because where I have studied them in mining-districts, either by personal observation or from the description of others, I find one or more of the evidences of compression present, viz., striation, brecciation or crushed material, and sheeting of the country-rock. Such complicated systems of fracture would appear to involve, as I

have already suggested, the action of more than one system of dynamic movement; that is, of forces of compression acting at the same time in several directions, and hence combining with the direct plicational strain more or less strain of torsion.

The effects of such torsional strain can be best understood by considering the effect of torsion alone. This is well shown in Daubrée's experiment upon a sheet of glass held firmly at either end, and subjected to a torsional strain up to the point of rupture. The following diagram, Fig. 1, showing the cracks thus produced in the glass, is copied from that in his *Géologie Expérimentale.*

It is to be remarked in regard to the cracks or fissures thus produced:

1. That they follow two general directions, crossing each other at a nearly uniform angle.

2. That certain cracks are more prominent and fully developed than the others, and often consist of groups of nearly parallel cracks.

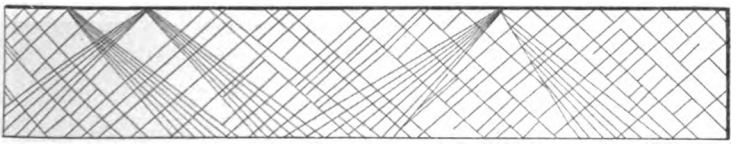

FIG. 1.—SHEET OF GLASS CRACKED BY TORSIONAL STRAIN (FROM DAUBRÉE).

3. That, among the subordinate cracks, some extend only from one of these greater cracks to the other, and do not continue on in the same line, but at a little distance on the one side or the other, so that they might appear to have been faulted or displaced by the larger crack, if one did not know that all had been formed contemporaneously and by the same strain.

In nature no such regularity or uniformity could be expected; and yet, when one considers the cross-joints of sedimentary rocks, it is surprising to observe how much they recall the lines in this diagram. In the larger joints or fractures observed in mining-districts, the effects of direct compression have been more marked, and the effects of the torsional strain are probably more seen in the minor fractures, or stringers and leaders, as the miners call them. Still, if one calls to

mind the map of a mining-district characterized by a multitude of small veins, it will be found that the more detailed the map and the more thoroughly the veins have been explored and represented thereon, the more regularity and uniformity in their directions are shown. It must be borne in mind, however, that such a map never represents the totality of the fissures in the district, but only such parts of them as have been found sufficiently rich to exploit for ore.

The following diagram, Fig. 2, represents the veins of a portion of the region around Freiberg, Saxony, as given on the official maps. Here two general directions are prominent, and combined with them are certain directions which would appear to be resultant of these two. Even more striking is the uniformity of system in the mining-districts of Cornwall, which have been worked for so many years that the various fractures are exceptionally well explored.

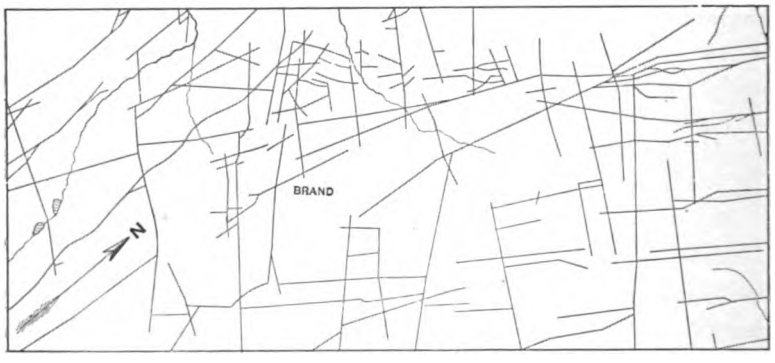

FIG. 2.—VEINS IN THE ERZGEBIRGE, NEAR FREIBERG, SAXONY.

The predominance of certain directions in the lines of fracture in these, as in almost all well-studied mining-districts, has been the subject of remark, and has given rise to considerable speculation; but generally this speculation has been based upon the idea that the veins were the filling of considerable open fissures by mineral currents coming from some unknown source below, and has been rather mineralogical than structural; that is, more attention has been given to the character of the filling than to the structural origin of the fissure. If all those who have described mines and ore-deposits had devoted as much and as intelligent study to the structural features of the regions

where they occur as the late von Groddeck did in the Harz, we should probably be much nearer a satisfactory theory of the origin and manner of formation of the ore-deposits than we are at the present day.

It is evident that by a succession of dynamic movements, especially when accompanied by torsional strains, an almost infinite variety of fissures and passages for mineral-bearing waters may be produced, and that it would therefore not be possible beforehand to describe all the various structural conditions under which ore-deposits may occur. It is only by an intelligent description of such fissure-deposits as are observed in nature in all parts of the world that we can get a comprehensive view of the various possibilities. Still there are certain conditions that suggest themselves as a result of the structural method of considering them that would seem to have a general application.

Structural Generalizations.—Extent of Fissures.—Since the dynamic movements are confined to the crust of the earth, it is evident that the fissures produced by them cannot literally have an indefinite extent in depth, though in certain cases it is very possible that this extent may be practically indefinite, as it may go beyond the limits at which mining is practicable. It is fair to assume that those fissures which have the greatest horizontal extent will have the greatest extent in depth; in other words, that their vertical and horizontal dimensions bear some sort of proportion to each other. If, therefore, as some have maintained, the vein-filling has in all cases been brought from some source at great depths in the earth, the greatest fault-fissures would be expected to be the greatest and most frequent ore-producers, since they would reach nearer to this unknown source.

In my own experience, however, I have found rather the reverse to be the case, which, as far as it goes, furnishes an argument in favor of the view that the vein-material has been derived from the surrounding, though not of necessity absolutely contiguous, rocks. On the great fold-faults I have found no considerable deposits of ore, and it is comparatively rare that continuous deposits are found along a single well-defined fault-fissure. The majority of deposits seem to occur where there are a series of fissures, more or less regularly co-ordinated,

in which several of the series are prominently accentuated. In such systems there seems to be a tendency for the rich ore-bodies or bonanzas to extend in a direction which lies at an angle with that of the main fissure, or to continue for a certain distance along one fissure and then to pass into another fissure, set off at a little distance from the first. It would seem probable that there must be some structural reason for the concentration of ore in this way, and that sufficiently wide and detailed studies might discover this reason and thus throw some light on this, at present, so obscure subject.

The practical lesson to be learned from the above phenomena is that the miner should not confine his explorations to the single fissure in which his ore occurs; but when he runs out of bonanza in that, he should seek a continuance of it in some adjoining fissure or plane, in a direction to be determined by the study of the system of the fracturing of the region and of the general direction of the bonanzas.

Vein-Walls.—The second generalization is in regard to the *walls*, which have generally been considered an important and almost indispensable characteristic of a true fissure-vein. The typical wall which the miner considers an evidence of a strong and well-defined fissure-vein is a comparatively smooth, generally striated, rock-plane, and frequently coated with a clay selvage—a band of decomposed argillaceous material which itself generally shows evidence of pressure and movement. From the above structural point of view of the origin of vein-fissures it is evident that the character of the wall and selvage is dependent on the composition of the rock and the amount of displacement and pressure. The grinding of one face of rock against another will undoubtedly tend to plane off both and to produce a certain amount of fine attrition-material; but this attrition-material will not necessarily be reduced to clay unless it has further been subjected to the decomposing action of water, which has carried off certain portions and left an argillaceous residue. The extreme instance of such decomposition is found in the muddy accumulations at the bottom of caves in limestone, which are simply the less soluble residues, mostly silica and alumina, resulting from the dissolution of large quantities of more or less impure limestone.

These walls and selvages are a frequent accompaniment, but

by no means an essential characteristic, of an ore-bearing fissure. It is quite conceivable that one or both may be wanting; and such occurrences are not uncommon in nature. Take, for instance, the veins of Butte, of which I gave a brief description at a former meeting.[9] These are a series of co-ordinated fractures or compression-fissures in a remarkably homogeneous mass of granite. Apparently there has been little or no displacement in the walls of these fissures relatively to each other; hence, but little attrition-material has been produced; and for this reason—and probably, also, on account of the character of the rock and because it was not much decomposed along the fissure-planes before the advent of the ore-bearing solutions—no clay selvages have been formed, and the ore-bearing solutions have eaten into the wall-rock to varying distances, replacing it more or less completely by vein-material, and leaving no definite boundaries or walls to the deposits. There is no reason, however, for considering them any the less true fissure-veins or less valuable ore-deposits on this account.

On the other hand, under certain conditions, instead of an absence of well-defined walls, there may be so many as to mislead the miner who depends too implicitly upon them as a boundary of his ore-body. In the Gunnison region above mentioned, for instance, where, owing to the plasticity of the country-rock, it has been divided along the main fracture-planes into a series of very thin parallel sheets, the space between these sheets has frequently been filled by quartz, which thus forms a thin sheet, often so completely reproducing the form of the fissure as to present a cast of the striation-surfaces. Such a sheet of quartz, when the adjoining bands of country-rock have been replaced by vein-material, forms a hard, well-defined wall to the ore-body, which delights the eye of the honest miner and enhances in his mind the value of his property.

Ore may be found as well on one side as on the other of such a wall, and not infrequently is apparently confined to one side for a considerable extent along the length of the vein, and then is found almost as exclusively on the other side. Thus, in one prominent mine in this district I found a drift run for several

[9] Notes on the Geology of Butte, Mont., *Trans.*, xvi., 49 (1887–88).

hundred feet in barren country, but following what was apparently the direct continuation of the vein which had been yielding a large amount of rich ore. After a change of administration in the mine, it was found by cross-cutting that there was a continuous ore-body only from 4 to 6 ft. to one side of this drift and parallel with it. In another mine in the same district, which had produced a great deal of very rich ore, I found that though there were frequent cross-cuts into the country on the hanging-wall side, disclosing the usual systems of parallel fissures, none had been made on the foot-wall side. The reason given was that this foot-wall was so uniform and well defined throughout the mine that it was considered useless to explore beyond, since it must necessarily be the limit of ore in that direction. An examination showed that there was no geological reason for this assumption in the character of the rock, and that it was simply one of a number of quartz-fillings between two sheets of country-rock. On visiting the mine a few weeks later, I was told that in the southern portion of the mine, where the vein had seemed to be running out at the time of my first visit, a new body of rich ore had been struck by cross-cutting into the foot-wall country.

The moral is that judicious cross-cutting forms a very important part of vein-mining, but should be conducted with due regard to the fracture-system of the adjoining country, and to the evidence to be obtained as to the course followed by the ore-bearing currents, or it may involve an unnecessary amount of dead work.

Banded Structure.—In most of the deposits of the Gunnison region, referred to above, there is a noteworthy appearance of banded structure parallel with the walls of the fissures. The evidence of faulting and of the thin sheeting of the country-rock is there so clear that the explanation at once presents itself that this appearance arises from the fact that the deposits are partly a filling-in of interstitial spaces, and partly a replacement of thin sheets of country-rock, the differing composition of the bands resulting rather from the necessary variation in the process of deposition than from essential differences in the ore-bearing solutions. Were one to examine there only a large body of rich ore, and neglect to examine the adjoining poorer deposits and to study the structural conditions of the region,

one might be led to adopt some of the complicated explanations set forth in books on ore-deposits, such as successive reopenings of the vein, to account for the conditions found, instead of the simple one given above. Reasoning inversely, I am led to think that much of the banded structure described in books on ore-deposits might be accounted for in this way, if the deposits could be re-examined with a view to determining the structural evidence in favor of it. For instance, in the excellent work of J. Arthur Phillips [10] there is given a diagrammatic section of a vein at Carn Marth, in Cornwall, consisting of six successive bands composed of quartz, with metallic minerals in some of them, separated from each other and from the adjoining country-rock by clay partings or selvages. The explanation there given to account for this condition of things is, that it is "a fissure that has been several times reopened;" and the author says, "It will be observed that each reopening has been attended by an amount of grinding action between the walls sufficient to produce a clay parting of considerable thickness." This explanation involves so much that is geologically improbable that I feel convinced that it is not the true one, and that some condition of things analogous to that described above might be found on examination of the mine itself. The clay parting might prove to be a more or less completely decomposed band of country-rock; for it is difficult to conceive that clay could be produced by the grinding of quartz on quartz. In reading such descriptions one has to bear in mind that in making a diagrammatic section one is liable, consciously or unconsciously, to bring out strongly points that are in favor of the explanation one has in mind, and to neglect those that are opposed to it. That there may be repeated or continued movements along the same fracture-plane cannot be denied, but, as will be argued later, one should not resort to such explanations for phenomena that can be accounted for otherwise.

Crushed Zones.—Thus far we have been considering mainly the sheet-like bodies deposited along fissures having a generally parallel direction. But cases must also occur where the systems of rock-fracture intersect each other, and under suitable conditions considerable portions of the country-rock included

[10] *A Treatise on Ore-Deposits*, p. 48 (1884).

between such intersecting fractures may be broken up or crushed to such an extent as to admit a relatively free passage of percolating waters. Where such waters are mineral-bearing, the interstices between the fragments will offer spaces for the precipitation of their contents, or where the rock is readily soluble the fragments themselves may be replaced by vein-material. The forms of ore-bodies thus deposited may evidently present much greater variety and irregularity than those deposited along single or parallel fissure-planes. J. S. Curtis, in his memoir on the Eureka district,[11] gives a detailed description of the extremely complicated and irregular zones of crushed limestone to which the ore-deposits there are practically confined.

Where three or more nearly vertical fracture-planes intersect each other near the same point, the prismatic body of rock included between these intersections may be so crushed and broken as, in a district rich in mineral-bearing solutions, to give rise to what are generally known as chimney-deposits. Where the fracture-planes are merely joints along which there has been but little movement, and consequently no clay selvages have been formed, the ore-solutions will eat out into the rock in such a way that the ore-chimney may appear to have a rounded instead of an angular horizontal section, and the fracture-planes themselves may have become, by the decomposition of the adjoining country-rock, so obscured as to be with difficulty traced in the immediate vicinity of the ore-body. Instances of deposits to which this origin may be ascribed are the Bull-Domingo and Bassick mines in the Silver Cliff district, and the Yankee Girl mine in the San Juan region of Colorado.

The first-named deposit occurs in Archæan rocks, traversed by a dike of compact syenite which in places forms one boundary of the ore-body. The ore is mainly galena, which constitutes the cementing-material of fragments of the country-rock resulting from the movement of displacement. These fragments are mostly of gneiss, and as this rock is readily decomposed by aqueous solutions, the fragments are generally rounded; the few fragments of the less readily attackable sy-

[11] *Monograph VII., U. S. Geological Survey* (1884).

enite, however, retain in great degree their original angular form.

The deposit of the Bassick mine is a nearly vertical chimney of somewhat square or lozenge-shaped outline, which has been explored to a depth of about 1,100 ft. from the surface. It occurs in an andesitic breccia, composed of angular fragments of various sizes and forms cemented together by material of essentially the same composition as the fragments. This cementing-material, probably by reason of its later consolidation, has been more readily attackable than the fragments, for the ore has replaced it, forming concentric layers around the fragments, whose angles have become rounded during the process of deposition. Here the fragments were original and not necessarily produced by the dynamic movements, which probably resulted in a simple fracturing of the rock without much displacement.

In the Yankee Girl there are several chimneys in which the ore occurs. They are of elliptical outline, the longer axis corresponding in direction with a main system of fractures running through the region. Although the striated surfaces of these planes show that there has been movement along them, there is but little evidence left of actual brecciation of the country-rock, the ore-solutions having completely replaced the andesitic country-rock between the fracture-planes which admitted them. In places a siliceous skeleton is left, the basic constituents being replaced by vein-materials; in other places a solid body of metallic minerals is found, while the country-rock adjoining the body of pay-ore is impregnated to a considerable distance with low-grade sulphurets.

Repeated Movements along Fissure-Planes.—It is a well-recognized fact of structural geology that in successive dynamic movements in the same region there will be a tendency for fractures to follow already-determined planes of fracture. Furthermore, it appears that the faulting of a rock-mass is not necessarily a geologically instantaneous movement, but that the displacement may continue for some time after the first fracture has been determined, probably dying out very gradually. Some such continued movement seems necessary to give time for the reduction by the action of water of the attrition-material to the clayey condition in which it is often found.

We may expect, therefore, to find evidence in large fissures of repeated movements. In the Comstock lode, for instance, which G. F. Becker[12] has so well demonstrated to be a great fault-fissure, accompanied by sheeting of the country-rock on a grand scale, the crushed and sugary condition of the quartz, which in the fissure has replaced the included masses of country-rock, can hardly be explained, except by movement along the fault-plane subsequent to this replacement, though perhaps prior to the final completion of the ore-deposition.

On the other hand, it is easy to conceive that the healing of a fissure, as we might regard the filling-in of its interstices by vein-material, might make it better able to resist fracture than it was before, and a second fracture in such a case would not necessarily follow the already-determined plane. Moreover, if we recall the diagram given on p. 51, showing the fractures produced by torsion in a sheet of glass, it will be seen that cross-fractures, and even apparent displacement of one fracture by another, may be produced by one and the same strain. Hence, in studying a system of fissures, one must not too hastily conclude that each direction of fracture means a distinct movement, or even that displacement of one fissure by another necessarily proves that the latter was produced by a distinct and later movement; to be sure of this, some of the other evidences of movement must be found.

The famous Ontario mine in Utah affords an excellent instance of a strong fault-fissure deposit in a region which has been subjected to repeated dynamic movements, associated with successive intrusions of eruptive rock, and illustrates the above-mentioned points. I had intended to submit detailed plans of the underground workings of this mine, drawn to scale, with the geological data indicated thereon, but find that the notes gathered somewhat hastily during my visit of last summer are not sufficiently complete for this purpose. I shall therefore describe, as clearly as I can in words, the characteristic structural features of the deposit.

It occurs in distinctly-bedded quartzites of middle Carboniferous age, which dip about 20° to the northward and strike here nearly east and west. These rocks are traversed by nu-

[12] Geology of the Comstock Lode, *Monograph III., U. S. Geological Survey* (1882).

merous bodies of eruptive porphyry, some in the form of dikes, others of irregular shapes. But few appear at the surface in the immediate neighborhood of the mines; they are mostly disclosed by the underground workings, many of the dikes having a direction parallel with the vein-fissure and sometimes forming one of its walls for considerable distances. An older dike is faulted by the vein-fissure.

The vein-fissure has a somewhat curving direction, running about east and west, or parallel with the strike of the formation, in the eastern part of its course, and bending towards the southwest in the west half. Its dip, however, is much steeper than that of the quartzites, being from 45° to 50° north, instead of 20°, so that it cuts these at an angle of from 25° to 30°. In the western part of the mine it is a double fissure, or, as the miners express it, there are two veins, a north and a south one. These are connected by what the miners call "cross-courses," which are smaller, co-ordinated, and nearly parallel fractures, forming an acute angle—about 30°—with the main fissures. These are regarded there, in accordance with generally-received ideas, as a distinct system of fractures formed at a different time from the main fissure. I find no geological evidence of this, however, either in the structural conditions or in the composition of the vein-material.

The fissures show plentiful evidence of movement in striations and crushed country-rock, the ore being a filling-in of the interstices between the quartzite fragments, and perhaps a partial replacement of the same. The principal fissure consists in places of a zone of broken quartzite, sometimes over 100 ft. wide, the ore being distributed in seams along the boundaries of this zone and crossing it along a somewhat irregular series of planes, but in which a certain co-ordination of system can be traced.

Three distinct series of dynamic movements can be traced in the structural condition of this mine. The first is proved by the existence of a narrow dike of older porphyry, crossing at right angles the western part of the vein-fissures, where the two members are about 600 ft. apart. This is locally called the trap dike, from its somewhat darker color than the other porphyry bodies. By the second series of movements the vein-fissures themselves were produced and this trap dike was

faulted and displaced. On the 600-ft. or drain-level of the mine this displacement can be observed in each of the principal fractures. The lateral or horizontal movement is about 40 ft., and, as the striation-surfaces across the face of the dike are inclined at an angle of about 45° with the horizon, it may be assumed that the vertical movement was of the same amount. The third dynamic movement is shown by what is locally called the "dislocating fissure," which runs in the same general direction with the western part of the vein, and on the drain-level is intermediate between the two veins, cutting and displacing the cross-fissures.

There are also large faults in the country-rock at both ends of the workings, which now have a linear extent along the vein-fissure of about 6,000 ft. I had not time to determine definitely to which period of movement these last faults belong.

A careful and accurate study of the structural relations of this most important mine, of which the above is only a hasty glimpse, gathered during a couple of visits to a part only of the underground workings, would form a most valuable contribution to our knowledge of vein-structure.

Another mine recently visited by me, whose structural conditions seem peculiarly instructive, is the Queen of the West mine, near Kokomo, in the Ten-Mile district of Colorado. It is situated on the steep southeast face of a shoulder of Jacque mountain, and the vein-fissure runs nearly parallel with this slope, or in a northeasterly direction, and has been explored to a length of about 2,000 ft. It stands nearly vertical, thus crossing about at right angles the sedimentary beds in which it occurs, and which have a slight dip eastward, or down the slope of the hill. These beds consist of sandstone, rather rich in feldspar, some shaly beds, and intrusive sheets of porphyry generally conformable with the stratification of the sedimentary beds.

The faulting of these rocks has taken place not along a single plane, but along a series of parallel and closely contiguous planes. In other words, by the dynamic movement the country-rocks have been divided into thin sheets, each of which has moved past the other a certain distance, and in the central part of the fissured zone the interstices between the sheets have been filled with vein-material and the sheets them-

selves decomposed, impregnated, and to a greater or less extent replaced by it. There results a condition of things which is extremely puzzling for the miner who expects to find his ore between well-defined walls. Walls there are in abundance, and of excellent definition at times; but no one wall can be followed continuously for any great distance. Experience has, therefore, taught those who are managing the mine, while they follow in their main drifts or levels as nearly as possible the center of the mineralized zone or vein, to run frequent and extended cross-cuts on both sides of this central drift, which have disclosed ore-bodies running parallel with it, now on one side, now on the other, and often from 15 to 25 ft. distant from it. The longer cross-cut drifts, which have been run 30, 50, or even 100 ft. into the adjoining country-rock, disclose a series of parallel fissures, in general farther apart as the distance from the central drift increases. Although mostly barren of pay-ore, they always give evidence of a certain amount of mineralization: sometimes they are filled by a vein of massive crystalline calc spar from a few inches to a foot in thickness. In the portion above the water-level, owing to the secondary decomposition of both ore and country-rock, and to the diffusion of metallic oxides which have stained the whole, it is often difficult to recognize whether partly-replaced portions of the vein-material were originally sandstone or porphyry. The outcrops of no less than four sheets of the latter rock have been traced on the surface; but, owing to the complicated movements along the fissured zone, there would appear at first glance to be many more there; for not only do the walls change from sandstone to porphyry and *vice versa*, in alternate levels, but on one and the same level one finds these rocks alternating with each other in an apparently unaccountable manner in either wall. One can conceive of such a thing as resulting from the movements described above, combined with the gentle inclination of the beds; but to represent it accurately on paper would require most full and accurate surveys and detailed studies along every drift, map in hand.

A second and apparently quite recent dynamic movement is evidenced by a faulting of the vein-fissures in the upper part of the mine. The displacement is slight in amount, and, what is rather unusual, it is along a nearly-horizontal plane. As this

plane dips gently east, it is probable that it is a movement along a bed of decomposed shale, rendered slippery by the percolating of surface-waters.

Similar horizontal faults along stratification-planes were observed by me in some of the gold-veins of the north slopes of Mt. Guyot, east of Breckenridge, Colo. By these the veins are faulted in a series of gently-inclined steps, only a few feet wide, the movement following the stratification-planes. The veins themselves are narrow cracks in a dense blue-black argillaceous shale of Cretaceous age. Owing to the insoluble character of the country-rock, there has been comparatively little replacement of it by the mineral-bearing solutions. Sulphurets of iron and gold have been deposited in narrow fissures, seldom over an inch thick, and by secondary decomposition the iron is oxidized and the gold left in the form of leaf- or wire-gold. Sometimes a mat of interwoven wires of gold, an inch thick and larger than the palm of the hand, is found. Small quantities of gold have been deposited along the minute natural joints of the shales also, so that extraordinarily rich placers have resulted from their disintegration and abrasion by atmospheric agents.

Many more instances of different structural conditions might be presented did space and time allow; but I think the above are sufficient to illustrate the main proposition which I wish to lay down, namely: that careful structural study of the district in which a mine occurs and of the manner in which the water-passages were formed, which originally gave access to the mineral-bearing solutions, is of the greatest importance to the mining engineer in his determination of the probable extent and value of a deposit and of the best method of exploiting it. Hence, that he must be something of a structural geologist, as well as a technical mining engineer.

No. 3.

Geological Distribution of the Useful Metals in the United States.

BY S. F. EMMONS, WASHINGTON, D. C.

(Chicago Meeting, being part of the International Engineering Congress, August, 1893. *Trans.*, xxii., 53. Here reprinted in extract only.)

THE first paper which appears in the published *Transactions* of our Institute is that read by our respected Secretary at its first meeting in Wilkes-Barre, in May, 1871. It is entitled The Geological Distribution of Mining Districts in the United States, and presents a brief but masterly review of what was known of the distribution of our deposits of useful minerals, particularly the metals, not only from a geographical but from a geological stand-point.

At the request of Dr. Raymond, I agreed, somewhat hastily, perhaps, to write for this occasion a brief sketch of the geological distribution of the deposits of the useful metals in this country, in the light of the increased knowledge of the present day. In the time given no personal investigation was possible, and as it was therefore out of the question to attempt to make anything that could be considered an original contribution to the history of our ore-deposits, I have been obliged to limit myself to an examination of such published data within my reach as bore upon this subject, and could be consulted in the brief time I have been able to give to it. Had the geological investigations undertaken by the Tenth Census been continued systematically by the United States Geological Survey or by the Eleventh Census, it might have been possible to make a fairly-complete review of the subject. As it is, the principal result of my examination[1] has been to show how very unequal

[1] It would occupy too much space to give a complete list of the various papers and authors consulted in this examination, and it must suffice to say that they have been found for the most part in the publications of the following organizations: Tenth and Eleventh Census, Director of the Mint, various United States and State Geological Surveys, American Institute of Mining Engineers, Colorado Scientific Society; and in the *American Journal of Science*, *American Geologist*, *Engineering and Mining Journal*, *Zeitschrift für praktische Geologie*, etc.

and in many directions extremely meager are the data of any kind that are available, and to demonstrate the great need that exists for a systematic investigation of this important subject by some scientific organization, for its field is too vast to be covered by any single individual, and such an investigation will be of little permanent value unless carried out on some uniform plan by which the relative accuracy of its results may be assured.

The utmost that I can hope, therefore, for the very imperfect, and from a statistical stand-point possibly somewhat inaccurate, review here presented, is that it may offer to other workers in the field a suggestion of lines of investigation that may be profitably pursued in the future.

In the 22 years that have elapsed since Dr. Raymond's paper was written, many important contributions have been made to our knowledge of the geological structure of the continent, but a great part of these contributions, especially in late years, have been rather in the line of modifications and reversals of preconceived theories, than in the firm establishment of new ones. We seem now to have removed most of the unstable stones from the foundation of our geological knowledge, and to be nearly ready to build up a permanent structure in the immensely enlarged field that progress in various lines has opened to us. In like manner the special study of ore-deposits and of their relations to geological structure, which had hitherto been rather neglected by field-geologists, has in the last decade received more attention, though perhaps not as much as it deserves; many false conceptions have been cleared away, and important progress has been made towards a more rational method of correlating their phenomena.

In the realm of eruptive or igneous rocks, the great change that has come about has been the gradual abandonment of the theory that the mineralogical or structural character of the rock is a criterion of its age. It is no longer a necessary conclusion, for example, that because a rock is a trachyte, rhyolite, or basalt, it is of Tertiary or later age. Well-defined rocks of types formerly classed as Tertiary have been found to be as old as Cambrian, and the petrographical character of a rock is now admitted to be dependent on other causes besides geological age. It still holds good that most of the so-called volcanic

rocks are of Tertiary or recent eruption, but many crystalline rocks, actually granitoid in structure, are also of Tertiary age, and it is now necessary for the geologist to determine the age of the various eruptives of each district by their relations to sedimentary rocks of known age.

From the internal structure of the eruptive rock, whether more or less completely crystalline, one can judge whether it has consolidated at considerable depths and under the pressure of great weight of superincumbent rock-masses, hence very slowly, or at or near the surface and with comparative rapidity. In many cases this furnishes a further aid in the determination of the relative age of different varieties of eruptive rock occurring in a given region.

As regards the origin of eruptive rocks and the determination of the natural order of succession of the many types distinguished by their different chemical and mineralogical composition, most of the theories hitherto held are gradually being discarded or merged into what may be called the theory of differentiation of igneous magmas, which is now being worked out by the more advanced petrologists in this country and in Europe, and which promises to throw important light upon the origin of ore-deposits also. It proceeds from what is known as Soret's principle, that in a cooling solution of a salt, the salt will concentrate in the parts of the solution which cool first, and reasons that in a molten rock-magma a similar separation or differentiation of substances may take place. For instance, it has long been observed that in eruptive dikes of moderate dimensions, those portions of the dike adjoining the walls, which, when the matter forming the dike was injected, may be supposed to have been relatively cold, have a finer-grained texture than the interior of the dike, and in certain cases there is a concentration of the more basic minerals composing the general mass in the outer zone or in different parts of the rock-mass. It is assumed that on a larger scale the different varieties of eruptive rock which belong to one general period of eruption in a given district and are, so to speak, consanguineous, proceed from one general molten magma in the depths of the earth; and that in this magma a chemical and mineralogical differentiation takes place by virtue of which each successive eruption of igneous rocks differs in character

from the one which has preceded it, according to laws not yet fully made out, but which, according to the preponderance of chemically acid or basic material, under varying conditions, produce in the erupted rock a corresponding preponderance of acid or basic minerals.

On the other hand, considerable advance has been made in the classification of the crystalline rocks, which were formerly all grouped indefinitely as Archæan. More detailed and systematic field-studies in the areas occupied by typical series of crystalline rocks have shown that there are several series that can be distinguished as originally sediments made up of débris of older series, with a greater or less proportion of eruptive material, in which there is evidence of the former existence of organic life, and which are older than the oldest known Cambrian beds, and younger than Archæan, the latter term being limited to non-clastic rocks, in which there is no evidence of life. Petrological investigation, in the light of the most advanced studies in this branch of geology, has shown the enormous capabilities of metamorphism, in that a crystalline and more or less schistose product may result from the alteration of either sedimentary or eruptive rocks, the original form of which may be entirely undeterminable if such rock cannot be traced continuously in the field to some less altered condition in which sufficient traces of its original character can be found to admit of its satisfactory determination. As a result of these investigations, so much discredit has been thrown upon the classification and subdivisions of Eastern crystalline rocks by Hunt and his school, which were based on petrological distinctions now shown to be unessential and local in their character, that, until the areas covered by them have been systematically and carefully studied, the relative age of different parts of the series must remain a matter of doubt. In a few cases, fossil evidence has been found in the Appalachian areas to show that certain crystalline beds are altered sediments of Cambrian or later age. In others, remains of organic life have been found which are older than any known Cambrian forms. In most cases, however, it can only be determined on stratigraphical grounds or lithological evidence that the rocks in question are older than any known Cambrian, and younger than the fundamental complex of non-clastic crystallines for which the term

"Archæan" is still retained. To these rock-series the general designation "Algonkian" has been given.

The Algonkian, as thus defined, necessarily includes a great many rock-series in different parts of the continent, which, in the absence of palæontological evidence, cannot be correlated in age, and whose relative succession must be determined in each geological province separately and by itself. They have been thus far systematically studied only in the Lake Superior region, where the new classification was first proposed by Irving and Van Hise. Here they consist of an aggregate thickness of over 60,000 ft. of rocks, in which three general subdivisions, separated by great unconformities or time-breaks, have thus far been recognized, the Keweenawan or copper-bearing series, which consists of sandstones, conglomerates, lavas, and tuffs, being the upper, and resting unconformably upon the two great iron-bearing series, the Upper and Lower Huronian, which include all the at present economically important iron-deposits of the region. Two, and possibly three, series of Algonkian rocks, each of great thickness, and some showing a large development of eruptive rocks, have been recognized in the Rocky mountains, but for the Appalachians, where geological study is rendered more difficult by the intense complications of structure, great metamorphism, and deep covering of weathered material and soil, it can only be said as yet that certain rocks hitherto called Archæan are certainly either altered Palæozoic or Algonkian, while of the greater part it remains for further study to determine whether they belong to either of these systems or may properly be classed as Archæan.

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Genesis of Iron-Deposits.

It has always been a matter of wonder to the geologist, as well as to the layman, how such enormous concentrations of metallic minerals as occur in the great iron-mines could be brought about, and whence their materials could have been derived. In the light of the more exact studies of modern times, the easy reference of such knotty questions to the "unknown source in depth" is no longer available, especially since, in the case of the Lake Superior deposits, the last stronghold of the little band of geologists who still maintained the erup-

tive origin of iron-ores, the careful and systematic researches of Irving and Van Hise have demonstrated that the supposed eruptive bodies of iron oxide have been deposited from aqueous solutions as replacements of carbonates, and that the eruptive contact-phenomena result from the fact that the inclosing rocks, instead of the iron-ores themselves, are of igneous origin.

That iron-minerals, such as pyrite, magnetite, and ilmenite, are frequent and almost universal constituents of eruptive rocks, is well known, but they occur as original constituents of the rock, that have formed within its mass more or less contemporaneously with the other mineral constituents, and not as later injections into an already consolidated rock-mass; whereas, critical studies of existing ore-deposits have so universally proved them to be of distinctly later origin than the inclosing rocks, that the burden of proof lies upon those who would maintain a contemporaneous origin for any particular deposit. The truly scientific method in the study of such questions, at the present day, is the reverse of that which was followed in the early days of geology, when, after the observation of a few isolated facts, some great geological mind was led to a general theory, and humbler followers were only too apt to do mild violence to nature in order to make her facts conform to it. It accumulates, year after year, a multitude of facts of patient observation, supported by studies with the microscope and in the laboratory, avoiding general theories, and only making such deductions in regard to local conditions as are supported by the overwhelming evidence of facts.

Although we are yet far from having a sufficient accumulation of facts bearing upon the origin of iron-ores to justify the putting forth of any general theory, it may be allowable in the present case to indicate the lines of research to which the facts that have lately been accumulated seem to point as promising the most remunerative results.

A great deal of light has been thrown upon the manner of formation of iron-ore deposits by the researches of Irving and Van Hise in the Lake Superior region, and by the discussion of replacement of limestones by iron-ores in general by J. P. Kimball. By both, the process of formation of workable iron-ore deposits is regarded as a concentration by the agency of

percolating waters, such concentration being influenced by physical or structural conditions, and localized, it may be, by a pre-existing nucleus of iron-bearing minerals as original constituents of the rock. The deposition is considered to be in very large degree a metasomatic replacement of the rock-material, and only to a very limited extent a deposition in pre-existing open cavities.

For the Marquette region, it is found that though the Lower Huronian carried iron originally, the concentration into workable deposits, of both this and the Upper Huronian series, was brought about subsequent to folding and erosion, and that hence the age of the deposits as such is Upper Huronian or later. Evidence is also found that the deposition was a secondary concentration from waters percolating downward along the paths of great water-channels until stopped by some impervious base. The original condition of the ore is regarded as probably iron carbonate, though it is admitted that this may have been a replacement of calcium carbonate.

In the Palæozoic limestones and shales of the Appalachians, the iron-bearing solutions appear in most cases to have been also downward-going currents, or water sinking from the surface under the influence of gravity, rather than hot ascending solutions. The original mineral was the carbonate or the sulphide of iron (pyrrhotite or pyrite), and instances are adduced where the limestones carry in their mass over 2 per cent. of iron carbonate, and in other cases pyrite is known to occur in about the same proportion. Whether these minerals were chemically or mechanically deposited with the limestones or were introduced subsequently remains to be determined, but it appears improbable that deposits (of sufficient size to constitute workable deposits) were formed simultaneously with the inclosing rocks by chemical precipitation from sea-waters.

If it be admitted, then, that our workable deposits of iron-ore are mainly concentrations of iron-minerals already disseminated in sedimentary beds, and that these concentrations have occurred in different forms and places according to varying local structural or chemical conditions, it still remains to be determined what was the original source of the iron in different regions, and why the concentrations are so much greater in one place than in another.

A line of investigation that seems to promise interesting results is suggested by recent researches by Swedish geologists on the formation of concentrations of titaniferous ore by the so-called differentiation process in basic eruptive magmas. In Sweden and Norway, according to them, actually workable deposits of titaniferous iron have been formed by differentiation within the eruptive magmas of labradorite, hypersthene, or olivine rocks. Van Hise had already suggested for the titaniferous magnetites of the eruptive gabbro of Lake Superior that in the crystallization of these rocks, before the magma had solidified, magnetite, which is one of the early minerals to separate, had slowly settled to the base of the mass by virtue of its superior specific gravity. But it is still questionable whether in this differentiation process gravity is a controlling influence, since in most observed cases it is evident that some other force must have influenced the concentration. Metallic concentrations in eruptive rocks have been observed before, the most remarkable of which is the body of metallic iron at Ovifak in Greenland. Although in these cases the ores may properly be said to be of eruptive origin, it may still be doubted whether their concentration as workable deposits is not due, in a measure at least, to secondary action, as has been observed in the case of the Lake Superior gabbros.

While, therefore, one may not necessarily expect to find economically-valuable deposits in such rocks, the question naturally suggests itself whether the occurrence of large areas of older basic eruptives, which in some parts contain a relatively large proportion of iron-bearing minerals, may not fairly be considered to be an indication that neighboring sedimentary beds may contain large concentrations of iron-ores, which have been derived from them. Where such basic eruptives are older than the beds, this derivation would be mainly mechanical, the ores being sediments resulting from the abrasion of the eruptives, more or less concentrated according to varying conditions of sedimentation. Where the eruptives are younger and have broken through or overflowed the sedimentary beds, the derivation would be mainly chemical, through leaching-out and redeposition by the agency of percolating waters.

While there seems to be some genetic connection between the greatest concentrations of iron-ore and considerable devel-

opments of ancient basic eruptives, important deposits also occur where no such relation can be traced. The frequent association of iron-deposits in the West with large bodies of eruptive diorite, suggests that though the very basic rocks would naturally afford the greatest amount of iron, even a relatively acid rock, like diorite, may contain concentrations by differentiation, which have yielded to the action of percolating waters and thus allowed their basic constituents to be transferred to easily-soluble rocks like limestone.

Since water is the principal agent in the final concentration of ore-deposits, it is important in searching for them to study the physical conditions which will favor its ready action both in taking up and in throwing down. In the Northwest, Van Hise has found an impervious basement a general favoring condition. This assumes downward percolation, but within the crust of the earth the circulation of waters may be in any direction, according to local conditions. It may possibly be safe to assume that iron-ores which occur mainly as oxides would have been deposited from oxidizing waters or those which come recently from the surface, and that pyritous ores would be more likely to bespeak a derivation from subterranean waters. Types of the former are furnished by the Lower Silurian ores which pass in depth into ferriferous limestone, and are apparently a concentration due to leaching by surface-waters, in which other minerals have been removed in greater proportion than the iron oxide. The so-called gossan-ores occurring in the eastern or metamorphic belt of the Appalachians, and which pass into pyritous ores in depth, would appear to be good types of the latter class.

Much remains yet to be done in the study of the structural relations of iron-ore deposits. One of the interesting problems is furnished by the line of magnetic deposits occurring, in Pennsylvania and southward, in limestones at the contact of Mesozoic sandstones, and frequently associated with trap dikes. If this prove to be a line of displacement, as there seems to be reason to assume, it would afford a natural water-channel for the collection of iron-bearing waters from various series of iron-bearing rocks, which would preferably collect in limestones, and more readily from their broken edges. Whether the function of the trap has been to furnish heat for magneti-

zation of the iron oxides, as has been frequently assumed, or to interrupt the ore-bearing currents and thereby induce precipitation, may well be the subject of further investigation.

There is reason to assume that the concentration of iron-ores in the more southern parts of the Appalachians, especially in the extremely complicated regions of the Carolinas, Tennessee, Alabama, and Georgia, will be found to have more or less intimate structural relations with the many fault-zones that abound there.

A careful study of the magnetite-deposits in Colorado is likely to throw some light upon the true genetic connection, if any exists, between the occurrence of this oxide and the vicinity of eruptive bodies. In the light of present knowledge it would appear that the iron-ores occur as magnetite in the vicinity of large bodies of eruptive diorite and as limonite elsewhere at the same horizon. It has been asserted, moreover, that there is no evidence of an intermediate hematite or limonite stage in the alteration from pyrite to magnetite. As against the theory that in these cases the formation of the magnetic oxide is due to the heat of the eruptive body, it is probable, in the opinion of the writer, that these ores have been concentrated since the eruption of the diorite.

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Genesis of Manganese-Deposits.

The same lines of genesis suggest themselves for manganese as for iron, but owing to its much smaller percentage as a constituent of original rocks, it will be less easy to detect the probable localities favorable for secondary concentration in workable bodies.

In this secondary concentration the study of structural conditions which would produce natural water-channels is equally important. It has already been observed that the manganese-ores of the southern Appalachians occur along a great faulted zone, and the frequent mention of breccia conditions in other deposits suggests that further study may show that the concentrations of this mineral, as well as of iron, have been along such lines of displacement more frequently than has been hitherto realized.

In the relative chemical behavior of the salts of manganese

and iron in terrestrial economy there are certain unexplained contrasts which would appear to offer remunerative results to those who would occupy themselves with its study.

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Genesis of Nickel-Deposits.

The frequent connection in nature of nickel and magnetic pyrites, and of nickel with native iron and magnesia, in meteorites and at Ovifak in Greenland, is suggestive of an intimate connection between the two metals in fused magmas. The frequent occurrence of its silicate ores in connection with serpentine and associated with chrome and magnetic iron has often been remarked by geologists and chemists as pointing to a genetic connection between these minerals and magnesian silicate rocks. It is to be noted, however, that both the silicate of nickel and serpentine are secondary products. Serpentine is known to result from the metamorphism of many rocks, both eruptive and sedimentary, most commonly from basic magnesian silicate rocks in the first case, and from calcareous sedimentary rocks. The silicates of nickel may well be assumed to have resulted from the secondary alteration of sulphides, if the assumption is correct, that in those cases where it so occurs in association with magnetic pyrites the neighboring basic eruptives have not yet reached the extreme of serpentinous alteration. As with iron, therefore, certain portions of basic eruptive magmas may be supposed to have been relatively rich in nickel-bearing minerals, and by secondary concentration these may have been transferred to the water-channels of adjoining rocks. The greater this alteration of the rock the greater concentration of nickel-ore, as a general rule, would one expect to find.

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Genesis of Copper-Deposits.

The observed facts with regard to copper-deposits seem to point to eruptive rocks as the original source of the metal, and to indicate that its original form in deep-seated concentrations or deposits was that of sulphide. There seems to be less ground for supposing it to have been generally disseminated in marine sediments than in the case of some of the other metals, though very strong arguments have been advanced by geolo-

gists of great ability in favor of the theory of its chemical precipitation from the waters of the Triassic ocean by the agency of decaying organic remains. Its concentration, either in sediments generally or in ore-deposits, seems to have been by chemical rather than by mechanical processes. The assumption that certain portions of eruptive magmas are exceptionally rich in this and associated metals furnishes a good working basis for explaining its concentration in most well-known ore-deposits. Its chemical behavior, especially in deposition, presents some peculiarities not always easy to explain. In its ready assumption of the metallic state, as in certain other actions, it resembles gold and silver. Pumpelly explains the absence of the baser metals in the Lake Superior deposits on the assumption that the copper has been reduced from its salts by protoxide of iron, which would not have acted on the salts of the baser metals, which would have been carried farther on; and that once reduced to a metallic state, the copper was in a condition of greatest permanence in presence of the usual reagents. To account for the unusual amount of metal in this region, there is an extraordinary amount of eruptive material to draw from, and unusually intense and long-continued action of metamorphic or alterative processes to produce the concentration. On Keweenaw Point, traces of sulphur are found in the melaphyre; and in two mines, copper occurs as sulphide associated with other metals. Other exposures of this same series of rocks, in Wisconsin and Minnesota, where no ore-deposits have yet been found, are said to carry small quantities of metallic copper, associated with sulphides of iron and copper.

It is worthy of remark that the native silver which occurs with the copper in this region is never alloyed, but separates from it by rolling.

The unusual richness in copper of the ores along the limits of the zone of oxidation in veins at Butte and in the Appalachians is readily explainable by the leaching-down of this metal and the removal of the less permanent salts of the baser metals. It is more difficult to account for the frequent sudden appearance and disappearance of copper at different parts of an unaltered deposit of mixed ores, as at Leadville and other places. There does seem to be a more frequent association of

deposits of gold and copper with relatively acid rocks, as of iron, chrome, and nickel with basic magnesian rocks, but exceptions are so frequent and data so incomplete, that it is questionable whether this association can properly be assumed to have a genetic cause. The pebbles in the copper-bearing conglomerate of Lake Superior, for instance, are said to be mostly of acid eruptives; but this may result from the superior hardness of these rocks over the altered basic rocks. In Leadville, the ores carrying copper in the most important deposits are in a more siliceous limestone than are those which contain no copper, but other copper-deposits in the same region are in the more pure magnesian limestone, and both here and in Arizona more copper is found in the relatively basic limestones than in the adjoining acid eruptives.

The presence of copper in nature is so easily detected on account of the bright colors of its surface alteration-products, that it may be assumed to have been so thoroughly prospected that no important sources of the ore remain undiscovered. It seems probable, however, that the belt of pyritous ores with limonite caps which stretches through the crystalline zone of the Appalachians, and contains generally small percentages of copper, may yet prove a source of this metal of commercial importance in connection with other products of these great deposits.

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Genesis of Lead- and Zinc-Deposits.

For the original source of lead and zinc there seems no valid reason why we should not look to the massive eruptive rocks, as in the case of other metals. It is true, that their mineral combinations do not form prominently-visible constituents of these rocks, as do the iron-bearing minerals, nor have concentrations of them yet been discovered which could be considered to be the result of differentiation in an eruptive magma. As their deposits are found in nature, they are essentially precipitations from aqueous solutions, and their favorite habitat appears to be sedimentary limestones. Moreover, for the very extensive and important deposits of the Mississippi valley there are no known eruptive rocks within reach from which their metals could have been derived, and the opinion of most of the

geologists who have made careful study of these deposits is that the metals in them were originally deposited with the limestones in a disseminated form, and that the present deposits are merely concentrations of these finely-disseminated minerals by downward-percolating waters. On the other hand, chemical analysis has detected their presence in appreciable amounts in some eruptive rocks not directly connected with ore-deposits, which is sufficient proof that portions of eruptive magmas may contain them as original constituents. If it is admitted that they were deposited with the Mississippi Valley limestones, whether chemically or mechanically, they must have been derived from some earlier rock-masses, and may well have resulted, either in first or second instance or even further back, from the disintegration or decomposition of older eruptive masses. The latest student of the Mississippi Valley deposits (W. P. Jenney), whose most detailed studies were made in the southeastern Missouri region, finds the fissures in the limestones to be fault-fissures, and argues that they are probably deep-seated, and that the minerals have probably been brought up through these fissures from some deep-seated source in crystalline or eruptive rocks below. The fact that, in the upper Mississippi region, blende, which is at the lowest horizon, is generally of earlier deposition than galena, might be considered an argument in favor of this hypothesis, though it is explainable otherwise. On the other hand, their general association with barite in Silurian limestones, and the fact that fluorspar is found with lead only in Sub-Carboniferous limestone, is in so far an argument of derivation from the limestones themselves.

In the West, the frequent association of the deposits with eruptive rocks is most striking, and it seems likely that more systematic studies in the Appalachians may discover a probable association of areas of concentration of their minerals with eruptives, from which they might indirectly have been derived. A most fruitful field of investigation lies open here, and one that is comparatively untouched, for no general truths can be derived from the study of a single deposit or group of deposits, and, as yet, the work either of individuals or organizations, in this country, has scarcely gone beyond this stage. It would also be interesting to determine how far the segregation of the

minerals of the two metals was due to differentiation in the original magma, and how far to a process of gradual selection in successive concentrations. In composite sulphide deposits of great extent, like those of Leadville, which may be assumed to be the first concentration after that in the original magma, there appears to have been a certain amount of selective segregation by which certain portions contain a larger proportion of one or of the other metal, comparable to the imperfect separation of the first part of an ore-dressing process. In the mineral economy of nature there is a generally-observed tendency for like to seek like, as far as freedom of movement admits. It suggests itself, therefore, that those deposits which contain one metal, to the practical exclusion of the other, may be the result of a succession of such selective concentrations, and hence more removed from the original source than the more mixed deposits.

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Genesis of Quicksilver-Deposits.

The original source of the quicksilver and the associated metals is believed to have been in or below the deep-seated granites. The deposits are regarded as having been precipitated from heated solutions containing sodium sulphide, rising through fissure-systems, by relief of pressure and contact with surface-waters. The quicksilver-minerals have been deposited in interstices between rock fragments and in masses of porous texture, particularly sandstones, but nothing like actual molecular substitutions or pseudomorphosis has been observed either in California or in Spain.[2] In the Bavarian palatinate, however, cinnabar has been found to play the part of a fossilizing mineral and has therefore replaced organic matter.

The only recent important development of quicksilver-ores in California is at the Mirabel mine, formerly known as the Bradford, in the Mayacmas belt, Lake county. This mine yielded in 1892, 3,245 flasks. The production at the older mines, and particularly at the New Almaden, has fallen to a very low point.

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[2] Data with regard to this metal are from G. F. Becker's monograph on the subject, 1888, and from private information communicated by him. He draws a distinction between molecular substitution and the deposition of ores in porosities which are due to precedent chemical action.

Genesis of Gold- and Silver-Deposits.

The frequent association of deposits of gold and silver with eruptive rocks, the world over, has long been remarked. Chemical investigation of many eruptive rocks has detected their presence under such conditions as leave little doubt that they were original constituents of these rocks. Recently a German geologist has reported the discovery of gold in a late eruptive rock in Chile, which could be actually seen, by the aid of the microscope, to be an original constituent of the rock. There seems very good reason to assume, therefore, at any rate as a working hypothesis, that the original or ultimate source of these metals has been the eruptive rocks.

With regard to their subsequent dissemination in sedimentary beds, whether by mechanical or chemical agencies, there appears to be less satisfactory evidence, as there are few known concentrations which can with much probability be assumed to have derived their material exclusively from sedimentary rocks. The concentration of the metals in workable ore-deposits has evidently been by the agency of aqueous solutions; detrital deposits are only the mechanical rearrangement of such concentrations, though some maintain that these have been enriched by precipitation from solutions.

Aside, then, from the study of the structural relations which would afford favorable conditions for the concentration of metal-bearing solutions and the precipitation of their contained salts in workable ore-bodies, which is of common interest and importance with regard to deposits of all the metals, a most fruitful field of research, and one which promises results of economic as well as scientific importance, is afforded by the study of the chemical and mineralogical affinities of these two metals, and their probable behavior under the conditions which may have existed where deep-seated deposits were formed. Much obscurity still exists as to the actual chemical condition of silver in galena and of gold in pyrite. The suggestion has recently been made that combinations of these metals, as alloys or otherwise, with small amounts of tellurium, bismuth, etc., are much more common in nature than has hitherto been suspected, and may be the reason of the unexplainable difficulties found in amalgamating certain ores, and further investigation on this line may produce important results. There are some

features, also, with regard to the behavior of these metals under the action of atmospheric waters, and their consequent concentration along the zone of alteration of sulphide deposits, which are not entirely clear, and demand more systematic and careful investigation.

Conclusion.

What is at present known about the distribution of ore-deposits west of the 100th meridian does not seem to call for any serious modification of the statement as to their general distribution made by Clarence King in 1870. It is probable that if the subject were carefully worked up in detail it would be found that the meridional zones laid out by Mr. King contain, as Raymond has suggested, a greater variety of minerals than he was at that time aware of.

In the eastern half of the continent it is evident, from the facts given above, that certain geographical areas are peculiar in containing great concentrations of certain varieties of minerals, but it seems hardly necessary to recapitulate the peculiarities of these areas, since it is the geological rather than the geographical distribution that is of practical importance. The former must have a genetic bearing; the latter can only have such bearing through geological causes. Unfortunately, our knowledge of the geological relations of the ore-deposits of our country is as yet too incomplete to afford material for any exhaustive generalizations on the geological relations of the useful metals as a whole, or the underlying genetic causes of such relations. The fissure-systems, or the natural water-channels which have admitted of the concentration of the metals into workable deposits, have, as pointed out by King, Becker, and others, certain definite relations with the great orographic movements, and these relations admit of our forming an idea of the relative age of the deposits. They do not, however, afford any reason why certain minerals are more prevalent in one district and certain others in another; nor do they necessarily afford any clue to the original source of the metals. A certain amount of systematic geological work has already been done by our Geological Surveys towards the solution of these important problems, which are of practical, as well as scientific, importance, but a vast amount remains yet

to be done, and many large fields are still practically untouched.

The suggestion afforded above as a working hypothesis seems to be one worthy of consideration by the workers in this field. If the metallic minerals do concentrate in eruptive magmas within the crust of the earth in accordance with some law not yet clearly known, but which results in what is called differentiation, by virtue of which certain areas of igneous rocks, formed by successive extrusions of material of differing chemical composition which have cooled at or near the surface, are found to be unusually rich in minerals containing a given metal or class of metals, a basis is afforded to account for the unusual abundance of deposits of these metals in a given area. In the case of the older eruptive rocks, the accumulation of mineral combinations of the metals into workable deposits may be the result of many processes of concentration, both mechanical and chemical. The concentration of material derived from younger eruptive rocks, on the other hand, would be more direct, and mainly chemical, by the sole action of percolating waters. In either case, did investigation prove that certain areas of eruptive rock were unusually rich in mineral combinations containing a given metal, it would afford reasonable ground for looking for valuable deposits of that metal in the vicinity, especially if the geological conditions of rock-alteration or metamorphism and dynamic movements are such as to favor concentration.

If sedimentary beds carry disseminated minerals, or concentrations of such disseminated minerals into ore-deposits, they might have been derived ultimately from the abrasion of bodies of igneous rocks rich in their minerals by differentiation. How close a proximity would constitute a vicinity would vary widely under varying geological conditions. It is quite uncertain how far percolating waters carrying minute amounts of metallic minerals in solution might travel through underground water-passages without depositing their load, but the possible distance is evidently very considerable; and the argument sometimes advanced against the lateral-secretion theory, that proof can be found in certain cases that the mineral of a vein could not have been derived from the immediate wall-rock, is no valid argument against this theory in its broader acceptation,

which admits the secretion from neighboring bodies of rock not necessarily in immediate proximity, but possibly at considerable distance and not visible at the surface.

For the derivation of sediments, the possible distance of the source of materials has still wider limits; but analogy from the conditions under which sediments are deposited in present oceans would bring it within 100 miles as a probable limit. Here, also, it may readily happen that the eruptive body from which the metallic minerals were derived is not visible on the surface.

Discussion.

(*Trans.*, xxii., 732.)

John A. Church, New York, N. Y.: It requires some courage to appear as a critic of a theory which is not only the fashion among American geologists, but is usually presented by them in terms which imply that any other views are an exhibition of ignorance. Still, I am obliged to say that the theory of lateral secretion as it is stated in this and other writings of Mr. Emmons and other geologists has not added much to our real knowledge or clearness of view. In the earlier and less developed stages of the theory, when it was used as Sandberger used it, to show that certain veins were probably derived from the rocks in which they lie, or which are adjacent, it was valuable in pointing us to an immediate source of ore-deposition. When we are driven to assume the existence of undiscoverable rocks at an unknown but certainly a considerable distance, and in an unknown direction from the vein, I do not see that we have improved upon the despised "unknown source in depth" with which our ignorance has been covered so long. The new theory may suffer from adolescence, and these points may be cleared up by further study, but I speak of it as it is.

Differentiation in a magma, by which a metal is concentrated in one member of a series of outflows, may explain why certain ores have favored a given locality with their presence; but it is not a necessary precedent to ore-formation. Concentration in the source of supply cannot be a requirement, for the forces that have been able to take up four or five tons of gold from an extensive body of rock must be able to collect

four or five thousand tons of lead, copper, or nickel from a proportionately more extended body of rock. That is to say, concentration is no more essential for these metals than it is for gold.

In fact, differentiation, as it is now explained, is not an advance upon old ideas, but a retreat from them. It was noticed long ago that violent eruptive phenomena, however long continued, died away in solfataras; and when a vein came to be looked upon as an extinct solfatara the inference was ready that veins are eruptive in the sense that the solfataric waters collected the metals from the unerupted residue of the magma and carried them to the veins. The early views carried differentiation further than the modern school.

It is the fashion of the new school, to which I believe all professional geologists in this country adhere, while all professional mining engineers keep themselves aloof from it, to speak of these old ideas as if they were very ignorant, and were necessarily brushed aside by the advance of experimental knowledge. It seems singular to me that the new school should recognize no other origin for ores than the leaching of rocks by comparatively shallow water-currents and yet recognize no other origin for the fissures that carry the ores than cataclysmic action! If it had been found that bed-planes were commonly the channels by which the ore-solutions entered, we might accept the fact as evidence of lateral secretion; but when I find the adherents of this theory declaring, as does Mr. Emmons (and as do all the others), that *every* ore-deposit lies in a plane of faulting, or has been filled from a fault, it seems to me hardly logical to carry one branch of the volcanic theory to such an extreme, and totally reject the other branch, with which this view is undoubtedly in sympathy.

The older geologists looked upon a vein as a channel established between the surface and the interior of the earth. Into its lower termination poured solutions, the character of which was determined by the pressure and heat normal to the depth at which they may have been formed. The almost uniformly siliceous filling of veins shows that this depth was uniform in its conditions of solution. It may have been the whole barysphere or only that upper portion within which we may imag-

ine a comparatively lively circulation. At least it was lower than the vein.

The crevice was supposed to be an open chamber, or series of chambers, with occasional points of support. Through this chamber the waters rose to the surface, where they were discharged. As they rose, they necessarily passed through zones of continually-decreasing pressure and temperature, and "relief of pressure" and "lowering of temperature" were the potent agents which were supposed to effect precipitation of the dissolved solids, discharge of gas being another. The idea that the rocks inclosing the crevice could act as precipitants received early attention, and has led directly to some of our most widely accepted modern ideas.

Undoubtedly, these are plausible views; and the agencies invoked are real agencies of precipitation, as we know from the action of hot telluric waters discharging upon the surface. One of our most noted veins—the Comstock—was studied and explained in the light of this older theory by Richthofen, in 1865; and these ideas have not been entirely abandoned there.

Mr. Becker, within the last ten years, has gone into an elaborate argument to prove that there has been almost no erosion of the Comstock rocks. If this argument is sound, the outcrop now is within 25 or 50 ft. of where the original outcrop was formed. It is true, his views contradict each other; and, if the dynamical conduct of the rocks had been what he describes, there would never have been an outcrop where the Comstock was found. Still, I believe all writers upon that noted vein, except myself, have represented it as a solfatara, in the sense that it was formed by hot waters from a deep unknown source discharging into the atmosphere. The attempts to connect lateral secretion with the lode have been failures; and the Comstock still represents the old theories in their advanced form. It seems to me, that the solfataric origin of ores is a more reasonable explanation of the observable facts, in some cases, than the theory of lateral secretion. That minute quantities of the metals are found in all or many rocks, is true; but the crucial question of their origin has never been determined. Do they form an original source, or a secondary deposition like the vein? is a question that has not been conclusively an-

swered; but I agree, and I think most mining engineers agree, with Posepný, in believing them to be the latter.

We owe to the distinguished author of this paper one of the most striking and valuable contributions to the discussion of the lateral-secretion theory. From his description we may say that, in his view, the ores at Leadville were not exotic, since the rocks in which they lie, the rocks from which they were leached, and the water-currents that formed them, were all at substantially the same depth. These features are essential to lateral secretion; for, if we allow that the circulating waters sink deep enough to reach the unerupted residue of the magma before they take up their metallic contents, we have the old solfataric theory of origin.

Sandberger's original idea, that veins are filled by leaching from the rocks that contain them, has been so expanded by the discussion of ore-bodies formed under a cover of three or four miles of rock, that it is brought, not into conflict, but into close sympathy with the solfataric theory. The question whether the origin was in erupted or in non-erupted magma is interesting; but it is not controlling when the action is acknowledged to have taken place at very great depth, far within the "barysphere" in either case.

Having reached that amount of agreement, it seems to me that the next task of the structural geologists is to determine critically whether any vein has really been formed in a crevice discharging directly into the atmosphere. The conditions found at Steamboat Springs and elsewhere seem to me to point to vein-action (if vein-action there is) at some other point. The discharging waters may be regarded as the filtrate derived from metasomatic precipitation lower down, or as a mixture of waters from the upper and lower regions. As yet, I doubt if we have any proof that ore carried by the deep circulation has been retained long enough to be deposited at the surface. Mr. Becker entertained that view, but I believe his conclusions upon the geology of the Comstock to be radically wrong.

ARTHUR WINSLOW, Jefferson City, Mo.: I think that others will join me in expressing thanks to Mr. Emmons for his admirable *résumé* of our ore-deposits, and for the many valuable suggestions embodied in it. The ground is so well covered

that there remains little room for additions, yet I should like to make a few remarks concerning some subjects touched on of which I have personal knowledge.

Mr. Emmons refers to the specular ores of southeastern Missouri collectively, as probably of Algonkian age. There is, however, a distinction to be made. Those of Iron Mountain occur in Archæan porphyry, in tongue-like masses or veins which taper out with depth. The ore of Pilot Knob, on the contrary, occurs as a bed interstratified with Algonkian clastics composed of débris of the pre-existing Archæan porphyries. These ores have recently been made the subject of renewed study by the Geological Survey of the State, through Mr. Nason. He thinks that the facts at Iron Mountain are such as to favor the theory that the ores there are derived from the decay of great thicknesses of porphyry, accompanied by a leaching-out of the abundant iron-content and its deposition elsewhere in crevices and openings of the same rock, at times possibly replacing the decomposed porphyry adjacent to these crevices. These deposits would thus be examples of chemical concentration from older basic eruptives. In the case of Pilot Knob, Mr. Nason concludes that the iron-ore body is probably the result of replacement of certain members of the Algonkian series of strata. This would again be an example of chemical concentration from an older basic eruptive, though if we allow that the Archæan specular ores were formed prior to the deposition of the Algonkian series here, it is possible that this Pilot Knob bed is of direct mechanical origin from the abrasion of these earlier ore-masses.

In the iron-deposits of central Missouri, which consist of a mixture of blue specular and red hematite ores, Mr. Nason concludes that we have instances of accumulation in cavities and depressions produced by subterranean erosion of limestone. The disturbed condition of the adjacent strata, their converging dips and other facts corroborate this. That there was some replacement of limestone by the iron-solutions is also undoubted. This is well illustrated by the recent discovery of crinoid remains in the body of the ores, replaced entirely by blue ore. An interesting fact about these fossil remains, and one which adds support to the theory that the ore accumulated in depressions or cavities, is that they are not fossils found in

the Cambrian country-rocks, but belong probably to a Lower Carboniferous fauna. All over the Cambrian area of the Ozark uplift patches and fragments of such later rocks are found, indicating that a thin covering once existed there, of which portions are preserved in depressions and pockets in the older dolomites.

Remote as these ore-bodies are from eruptive rocks, we are obliged to seek for their source in the surrounding sedimentaries. Mr. Nason has fixed upon the sandstones of this area as the probable contributors. These are often highly ferruginous, and are readily leached by percolating waters. It is probable that the decaying dolomites also contributed a share.

In referring to the zinc- and lead-ores of Missouri, Mr. Emmons has brought forward for discussion a series of most interesting and at the same time most perplexing deposits, so far as a satisfactory theory of their origin is concerned. Those of the southwestern portion of the State occur essentially in the Mississippian or Lower Carboniferous limestones. The statement that they extend into the Coal Measures should be made with limitations. They are found in shales of that age in Jasper county, but those shales are in isolated patches, which occupy depressions in the older ore-bearing Mississippian rocks. Hence, the metallic contents of the shales may be derived, by some secondary process of transfer, from adjacent ore-bodies. In any case, the Coal Measures in the State, as a whole, are practically destitute of these ores, which, therefore, can hardly be declared to belong to that formation, whether their general absence from it be due to their prior formation, or to limitations in their distribution determined by physical causes.

Cross-fissures or fault-fissures in these Mississippian rocks, to which Mr. Emmons alludes, if they exist, are not very apparent. The strata are, undoubtedly, very much shattered in certain limited areas, have been subjected to extensive subterranean erosion and corrasion and great silicification. Of a system of extensive or considerable faults, recent stratigraphic work in this region has, however, revealed nothing.

In the Cambrian limestones of the eastern part of the State, the conditions are somewhat different. Crevices and fissures are there plainly developed, and evidence of considerable fault-

ing is indubitable. In Franklin county, such vertical crevices have supplied large quantities of ore. In that portion of the Southeast to which Mr. Emmons especially refers, however, and which has produced by far the greater part of the lead, the crevices are of insignificant dimensions, and the experience has been that they contain, themselves, little or no ore. On the contrary, the great ore-masses consist of galena disseminated through a thickness of the country-rock often of 50 ft. and more. At Bonne Terre, a tract 1,300 ft. long by 800 ft. wide has been mined out of such diffused ore.

The crevices which traverse this ore-body are frequently almost blind, and can only be detected by the drip of roof-water. These are such as traverse almost any massive rock. They have possibly had their influence upon the ore-deposition; but to picture them as veins and channels of direct ore-supply seems hardly justifiable, even under the existing differences of opinion among geologists as to just what a vein is. The questions of the source and mode of accumulation of these ores are very broad, and involve considerations of the ore-deposits, and of the geological history of the whole Mississippi valley. Only through studious, detailed analytic methods can a satisfactory solution be reached. I hope, at a later date, to have something further to contribute to the Institute on this subject.

Concerning the distribution of barite, to which Mr. Emmons refers on page 78, I would add, that it is not confined to the older Cambrian rocks of Missouri, but is found in Cooper and adjacent counties, at a number of localities, in Lower Carboniferous limestones, sometimes associated with lead-ores. In a previous paper, presented to the Institute,[3] Mr. Emmons has suggested the use of the apparent fact of the limited distribution of barite in determining the origin of the ores. This occurrence in the Lower Carboniferous lessens the value of the suggestion, though it remains still locally serviceable.

MR. EMMONS: I am very glad to have the details which Mr. Winslow has given us with regard to the ore-deposits of Missouri; and as my knowledge of the greater part of them is

[3] *Trans.*, xxi., 41 (1892-93).

derived, not from personal observation, but from the descriptions of others, I am quite willing to accept his corrections of my facts, since his information is of later date than that to which I had access. I was aware that barite occurs at times in the Lower Carboniferous limestones of the Mississippi valley; indeed, small amounts have been found in the fluorspar-deposits of Rosiclare, Ill., since I wrote my previous paper to which he refers; but I think it still remains true that fluorspar is characteristic of the one horizon and barite of the other.

(*Trans.*, xxiv., 755.)

WILLIAM HAMILTON MERRITT, Toronto, Ont.: With reference to Mr. Emmons's remarks on the nickel-deposits of Sudbury in the district of Algoma, Province of Ontario, Canada, and his general argument in connection with igneous rocks as the source of supply of ores, I would draw attention to two series of facts personally observed in connection with the Sudbury deposits.

1. *The Diorite as a Source of Supply.*—The diorite, as a rule, is speckled with pyrrhotite, and to a less extent with chalcocite. In the diorite I have seen a speck of free gold quite visible to the naked eye. The same diorite, decomposed, has been run through a prospector's stamp-mill in an earthy and gossany state, and free gold and the new platinum mineral, sperrylite ($PtAs_2$), perfectly crystalline, have been collected from it. Near by, a quartz vein, cutting the same diorite formation, has yielded rich samples of free gold, which occurs also in the diorite walls beside the vein, the wall-rock being, in some places, thickly interlaced with threads of gold.

2. *Secondary Action in Concentration Has Produced Some of the Ore-Bodies.*—As has been noted by Mr. Emmons, the theory of differentiation, or the concentration of the ore-bodies in the fused magma, is offered to explain the source of the Sudbury nickeliferous pyrrhotite masses in the intrusive diorite. This would not appear unreasonable. Yet I am satisfied that a secondary concentration must have taken place to explain the presence of some of the ore-bodies; at all events, where the contents of copper run comparatively high. The presence of the horses of country-rock cemented by the ore (alluded to by

Mr. Emmons), and which I have observed sharply brecciated, seems to strengthen this belief; for if they had been floating in a fused magma, surely all abrupt demarcation would be obliterated.

Moreover, I have seen such signs of secondary action as thin films of native copper in connection with the ore-body; also a band of "fluccan" cutting across it, which may indicate a portion of the chief channel which may have filled the cavities caused by movement. Native copper grains are also seen in the crystalline hornblende rock associated with the deposit. I have not observed serpentine, which might be expected to occur. In another portion of the same ore-body there is free gold visible in chalcopyrite; and where a very small crack or vug had occurred in the ore, wire-gold has been developed. The ore-body is distinctly more quartzose than the diorite in which it occurs.

No. 4.

The Torsional Theory of Joints.

BY GEORGE F. BECKER, WASHINGTON, D. C.

(Virginia Beach Meeting, February, 1894. *Trans.* xxiv., 130.)

Complexity of Rock-Fractures.—The strains to which rocks have been subjected are manifestly very complex, and it is entirely safe to presume that every possible mode of deformation and rupture is exemplified. The most superficial inspection of any ordinary mountain region is sufficient to assure the observer that the rocks have been pressed, stretched, bent, buckled, twisted, and shorn. The study of torsional rupture cannot fail, therefore, to throw light on geological phenomena. The question is, how areas which have been broken in this manner are to be distinguished from those which have yielded to other systems of forces.

Phenomena of Joints.—It is well known that a large part of the more homogeneous rocks and some very heterogeneous rocks are intersected by partings, often called joints. These partings are frequently flat surfaces, even when seen in very large exposures, but are sometimes surfaces of moderate single or double curvature. Joints usually occur in groups, in each of which the several partings are parallel to one another, and several such groups often intersect the same rock-mass. In such cases the different systems make large angles with one another. Nearly all students of the subject of jointing have reached the conclusion that joints are faulted surfaces, the dislocations usually being of small amplitude; and this conclusion receives abundant support from the study of thin sections under the microscope. It has thus been shown that much even of what would be regarded in hand-specimens as mere slaty cleavage consists, in reality, of innumerable microscopic faults. For this reason, Mr. Daubrée rejects the term "joint," as failing to imply the existence of relative motion, and has introduced the terms "diaclase" and "paraclase" as substitutes.[1]

[1] *Bulletin de la Société Géologique de France*, Third Series, vol. vii., p. 108 (1879).

Although the word "joint" does not imply relative motion, it does not necessarily preclude such movement, and, as it is universally intelligible, I prefer it. In nearly all cases where joints are suitably exposed they show slickensiding. In many hundreds of joints I have found polished surfaces, although the throw of the faults was so small as scarcely to be determinable. Slickensiding is a very important genetic characteristic of joints, for wherever it prevails over any considerable portion of the parting, it is good evidence that the joint-walls have not only undergone relative motion, but have remained in contact during the dislocation.

It does not follow that gaping joints should be infrequent, for a rock-mass once affected by joints will present but small resistance to any disturbing force, and such a force may readily spread the joint walls.[2] Indeed, it is somewhat surprising that joints are so often found closed. When a bar of metal is cut by shears, the two parts are in contact immediately after the continuity is destroyed and they slickenside one another, but under ordinary conditions they then fall apart. The comparative rarity of gaping joints is explicable in part by the presence of water. The surface-tension of thin films of water leads to adhesions which seem to me of much importance. Thus, if two surfaces of rock are distant 0.01 in. from one another, and if the space is filled with water, the rock-surfaces are drawn together, in consequence of the surface-tension of the liquid, with a force equal to 13.5 lb. per sq. ft.; and if the opening is only 0.001 in. wide, the pressure will be 135 lb. per sq. ft.[3] There can be no doubt that many jointed rock-masses, which project above the local water-level, are prevented from disorganization by this means.

Explanatory Hypotheses.—Jointing is now regarded by all investigators as of mechanical origin. It has been referred by

[2] Prof. William King, *Transactions of the Royal Irish Academy*, vol. xxv. (1875), has collected much evidence to show that joints were originally close. Mr. Daubrée also draws from observations by himself and others the conclusion (*l.c.*): "A cutting or shearing force, then, was operative during the formation of joints." This is equivalent to asserting that contact existed during and immediately after rupture.

[3] The pressure is equivalent to that of a column of water, the height of which is c centimeters when the distance of the surfaces from each other is d centimeters, and $c\,d = 162/981.4$. Compare Tait's *Properties of Matter*, p. 258 (1890).

eminent authorities to simple tensile stresses, but observers have long protested against this explanation, because such joints would gape from the start and would not be slickensided. Even if a tensile stress leading to rupture were associated with slipping, slickensides would be produced only on a few small portions of the surfaces involved. These surfaces can never be true mathematical planes, and a rupture like that just suggested might bring into contact protuberances, however small, but in such cases slickensides would be confined to small portions of the surface. In heterogeneous masses, particularly in conglomerates, tensile stresses leading to rupture would produce rough and irregular partings. Even in masses so homogeneous as steel, tensile rupture takes place on very uneven surfaces.

For these reasons, jointing has been explained most satisfactorily by reference to pressure, though it does not follow that all jointing is thus brought about. Mr. Daubrée has shown by direct experiments with simple pressure that all the more usual phenomena of joints can be artificially produced, the line of pressure making an angle of about 45° with the joint-planes. In this case the immediate cause of the jointing is shearing stress, and the walls of the joints are not only in juxtaposition, but are pressed together during the rupture and dislocation. The dynamic theory of this case is not difficult even when the strains are finite and the angle between the joint-surfaces is greater than 45°.[4]

Some geologists hesitate to accept the explanation of jointing by pressure in a given direction, on the ground that an accompanying lateral pressure of sufficient intensity would preclude rupture. It is a very important truth that, under proper conditions, rupture cannot, and flow must, take place. A mass may be subjected to such confining forces that rupture is impossible by any deformation or change of volume; but this is true of tension, torsion, or shearing as well as of simple pressure. Since rock-fractures are abundant, it is certain that conditions permitting of rupture, as well as those compelling flow, have frequently prevailed.

While Mr. Daubrée and others refer many joint-systems to

[4] *Bulletin of the Geological Society of America*, vol. iv., p. 57 (1892).

the action of pressure, the famous author of the *Études Synthétique* has also made beautiful experiments on the torsion of glass plates, which produces systems of fractures highly resembling joints in their distribution. He has consequently expressed the opinion that torsion, as well as pressure, has led to joint-systems.[5]

Character of Torsion-Fractures.—Mr. Daubrée has minutely described the phenomena of the rupture by torsion of glass plates, these being mounted on paper to avoid the scattering of the fragments. Torsion, as he describes it, produces two main sets of fractures, approximately at right angles to one another, and usually at nearly 45° to the axis of torsion. The fissures cut the broad surfaces in lines which are nearly straight, and the surfaces of fracture are approximately warped surfaces, the inclination to the vertical in some cases reaching 50° on each side. Some few fissures reach from edge to edge of the plate, while many do not entirely cross it, and sometimes single fissures neither reach the edge nor any other crack, and are thus isolated in the mass. The fissures which reach the edge of the plate cut the narrow face at angles with the line measuring the thickness, which varies greatly—from 20° or less up to 50° or thereabout. Besides the more regular systems of parallel fissures, fan-shaped groups are not uncommon. In the neighborhood of the finer groups of fissures the glass loses its optical and thermal isotropy.

By the kindness of Prof. T. C. Mendenhall I have been enabled to make experiments similar to those of Mr. Daubrée in an apparatus which permits of gradually straining the plates and of measuring the angle of torsion. Besides common window-glass, I employed glass ground on one side, for the purpose of making sure that surface-tension played no part in the result. Well-polished plate-glass was also used, sometimes in simple strips and sometimes cut in the shape of a cross-section of an I-beam, in order to confine the initial rupture to points remote from the jaws. In a large number of the experiments the cut edges were ground with emery, so that imperfections of the edges might not influence the result. Many

[5] W. O. Crosby also adopts the torsional hypothesis, with the modification that he supposes the final rupture to be determined by shock.—*American Geologist*, vol. xii., No. 6, p. 368 (Dec., 1893).

different dimensions were selected, and the plates varied from nearly square rods to sheets wider than they were long. It was found best to substitute a thin fabric, known as "cheese-cloth," for the paper on which Mr. Daubrée mounted his plates. The paper, in drying, exerts a considerable tension, and the specimens mounted on cloth, besides being more easily handled after fracture, show smaller tendency to fan-fracture.

All of Mr. Daubrée's descriptions are illustrated by my specimens,[6] and I have but few observations to add. It scarcely requires mention that the curvature of the surfaces of rupture is ordinarily such as to permit of the free torsion of the broken plate. Sometimes, however, short cracks extending from the main fissure to the edges of the plate are so warped as to obstruct torsion. Hence, when the axis of torsion is not in the vertical, all the principal faults produced in the experiments are reversed, the hanging-wall rising relatively to the foot.

When the breadth of a glass plate is large relatively to its thickness, the surfaces of rupture are, as Mr. Daubrée remarks, nearly coincident with warped surfaces; but when the breadth is only a few times the thickness, the departure of the surface from a warped surface is well marked. In such cases it is interesting to note that *one* cropping of the fissure is usually wonderfully straight, while that on the opposite side is an inflected curve. From the point of view of pure dynamics the exact shape of these surfaces would be interesting, but I have reason to believe that the geometrical character depends essentially upon that of the cross-section of the twisted bar; and since it will seldom or never be practicable to determine the shape of a twisted rock-mass, there seems no geological interest in ascertaining the precise form of the surface of rupture. It is probable that the forms are all closely related to the warped surface.

Among the excessively fine cracks in the glass which are mentioned by Mr. Daubrée, there are some which are superficial. These are usually near the middle of the plate; they are very straight, and invariably parallel to the straighter edges of the ruptures on the same surface, and do not seem to pene-

[6] I have not tested the anisotropy in the neighborhood of the terminations of cracks not crossing the plates. As the mass at such points is in a permanent state of strain, anisotropy is to be expected.

trate quite to the center of the plate. They are clearly incipient fractures, and the observations indicate that rupture begins on one of the broad faces in a very straight line, the surface twisting as it spreads through the plate in such a manner as best to relieve the torsional stress. Even on rather thin plates it is visible that one cropping of each well-formed crack is straighter than the cropping on the opposite face, and that the straight cropping has a definite relation to the direction of twist. When torsion is so applied as to tend to twist the bar into a right-handed screw, the straight lines are inclined like the thread of a left-handed screw, and *vice versa.* Thus the straight croppings on one surface of a plate are at right angles to the straight lines on the other side of the plate.

The angles at which the cracks cross the narrow edge-surfaces of the plate vary considerably, as Mr. Daubrée has observed. I cannot find that the inclination of these lines varies in any regular manner with the width of the plate. The average angle which the cracks on these narrow surfaces make with the long edges seems to be about 63½°, or the angle whose tangent is 2. These croppings are in fact curved lines in almost all cases, and the curvature is such that the acute-angled fragments bounded by the edge of the plate and the ruptures are somewhat grooved.

The following diagram shows two warped surfaces intersecting a bar supposed four times as wide as it is thick, and a sketch of two of the more complex surfaces, referred to above, generalized from a considerable number of cases.[7]

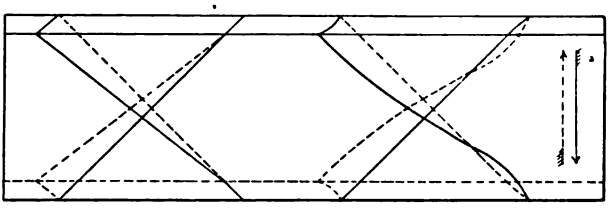

FIG. 1.—DIAGRAM ILLUSTRATING INTERSECTION OF SURFACES OF RUPTURE WITH A BAR.

[7] If the axis of the bar is the x axis, y the distance from this axis parallel to the broad surface, z the distance parallel to the narrow surface, b the breadth, c the thickness, then the following equation represents both the warped surfaces.

$$x = \frac{yz}{b} \pm \frac{y}{b}\left(b + \frac{c}{2}\right).$$

Rupture by Shear.—In a pure (or irrotational) shear the resultant load on any section passing through the center of the strain ellipsoid is the same. On the sections perpendicular respectively to the greatest and least axes the load is wholly normal. On the sections of unchanged area (which stand at 45° to the greatest and least axes when the strain is very small) the load is purely tangential.[8] In a homogeneous mass thus strained, rupture may conceivably occur by the tension along the greatest axis, or by pressure along the smallest axis, or by tangential motion at 45° to the axes. A mass ruptured by tension sometimes breaks perpendicularly to the direction of tension with a smooth surface, and sometimes, as in the case of mild steel, with a rough or "cupped" surface, the facets of which are in the direction of the planes of unchanged area. A mass broken by uniformly-distributed pressure breaks in the direction of the planes of unchanged area. A mass ruptured by tangential stress also breaks on these planes. Thus a homogeneous mass subjected to a shear can break in only two ways, viz.: perpendicular to the greatest axis or at 45° to this axis. In the present state of knowledge concerning the constitution of matter, experiment only can determine which rupture will occur. The experiments on glass plates in connection with the theory of torsion, due to the genius of Barré de Saint-Venant, render a decision very easy for this substance.

Points From the Theory of Torsion.—When a rectangular bar of an elastic, homogeneous solid is twisted through a small angle the following conditions are fulfilled: The lateral surfaces of the bar become warped; the length of every edge remaining substantially unchanged, while diagonal lines are elongated or contracted, but the volume of the mass is neither increased nor diminished by a sensible amount. At the surfaces of the bar the resultant strains lie in these surfaces. The directions of maximum extension and compression are at 45° to the axis of torsion, and at right angles to each other. If the rotation of the torsion-couple is positive (opposite to that of the hands of a watch) the directions of greatest extension on all the sides are inclined in the same sense as the thread of a right-handed screw. The strain at any point in the mass is a pure or

[8] *American Journal of Science*, Third Series, vol. xlvi., No. 275, p. 339 (Nov., 1893).

irrotational shear. The points of maximum strain are on the surface and nearest the axis; in other words, the danger-line is the median line of the broad surface; and on the narrow surface of the prism the strain is also greater half way between its long edges than elsewhere.

Most of these conclusions can be exemplified in a very easy and striking manner with a rectangular bar of rubber, such as is in common use for erasing pencil-marks. The surface of such a mass, cross-hatched with lines parallel to the edges, shows, when the bar is twisted, that deformation is greatest nearest the axis and insignificant near the edges of the prism. Lines at 45° to the edges are greatly extended or shortened by twist, and a very small circle is converted into an ellipse with axes at 45° to the edges.

It evidently follows that rupture should begin at the middle of the broad surface. If rupture takes place by slipping on the planes of no distortion of the shear ellipsoid, the cracks of the broken mass will be parallel to or perpendicular to the axis of torsion. If the mass yields to the tensile component of the shearing stress the cracks will coincide in direction with the lines of greatest linear compression and stand at 45° to the axis of torsion. This is precisely what occurs in the experiment on glass. On the other hand, the theory shows that the resultant stresses within the body of the plate are not in general parallel to the surfaces, and it is therefore to be expected that curved surfaces of rupture should ensue.

Character of Torsional Rupture.—It now appears certain that the experiments on the torsion of glass are equivalent to the application of a system of tensions peculiarly distributed, and that the fissures produced by torsion in any mass physically resembling glass, will exhibit the peculiarities of tensional fractures, together with some marked characteristics of their own. The fissures will gape from the start, excepting at certain points, which alone will be slickensided. The surfaces will be rough, excepting when the mass is uncommonly homogeneous. The surfaces will also show double curvature, which will be very strongly marked unless the mass of rock affected by torsion is immense. If the axis of torsion is vertical the particles originally in contact will separate along horizontal lines, and there will be no faults as these are usually estimated.

In all other cases every surface will be faulted, and every master fault will be reversed. The network of fissures will show marked regularity, provided that the exposure is an approximately flat surface nearly parallel to the axis of torsion, but any section forming an angle with the axis of torsion, will expose a very complex arrangement of curved partings. If rocks break under torsion at all as glass does, a pronounced characteristic will be the frequency of fissures completely "cut off" by others, these being much more numerous than "master" joints.

Conclusion as to Jointing.—It appears from the foregoing that though torsional rupture may be of frequent occurrence in disturbed regions, the systems of dislocations familiar under the designation of joints cannot aptly be ascribed to pure torsion, while direct pressure will produce the phenomena called jointing. But the forces acting upon a rock-mass are in general very far from simple; indeed, it may be assumed that every variety of stress exists in a strained rock-mass. Nevertheless a general idea of the nature of rupture even under such conditions may readily be reached. The strain ellipsoid at any point must either be torn apart by tension or cut across by shearing, and in all ordinary cases it is easy to distinguish these modes of rupture. In a mass subjected to a complex stress the orientation of the strain ellipsoid will vary from point to point, and so will the direction of the rupture; but smooth, slickensided surfaces, though curved, will still be due to pressures acting at approximately 45° to the local direction of the surfaces when the material is a hard and homogeneous one; and tension-cracks will form at right angles to the local direction of the effective tension. Thus in typically jointed areas, curvature of the joint-planes indicates that the direction of the effective pressure has varied from point to point, as it does, for example, in the compressed portion of a flexed bar. The existence of curved joint-planes is consequently by no means inconsistent with the ascription of jointing to pressure, while it does indicate that the entire system of forces, operative and inoperative, which has been brought to bear on the mass is complex. The action of pressure on heterogeneous materials is much more regular than the action of tension; and it might be possible in some cases from the study of curved joint-surfaces to infer the nature of the complete stress-system.

Discussion.

(*Trans.*, xxiv., 863.)

H. M. Howe, New York, N. Y.: It is, of course, not easy to discuss offhand the paper which Mr. Becker has presented with so much lucidity. I will make only one remark, which is outside of the line of his argument, and concerns merely a passing allusion in his paper. Mr. Becker speaks of the fact that glass breaks with a flat or conchoidal fracture, and that steel shows a rough or "cupped" surface of fracture. This difference we would naturally ascribe to the great difference in the other physical properties of the two substances. Yet I have seen copper-steel which did break in a perfectly flat fracture, or apparently so. It seemed to be accurately perpendicular; a smooth, mirror-like fracture, such as mineralogists called "splendent." Yet the physical properties of this steel did not differ from those of common steel, or resemble those of glass in the way which this fracture suggests.

R. W. Raymond, New York, N. Y.: The general conclusions reached by Mr. Becker seem to me to be fairly demonstrated. His paper does not contain any precise definition of what we call joints; and possibly such a definition ought to be offered as the basis of any complete theory of the subject. Without venturing to supply such a definition here, I infer from Mr. Becker's paper, and in accordance with our general usage of the term, that joints are to be distinguished, on the one hand, from cleavage-planes, which we may, perhaps, consider as potential rather than actual partings, and, on the other hand, from fissures on a larger scale, such as become the receptacles of mineral veins. And I understand his view to be, that jointing is neither produced by tensile stress nor by pure torsion, while direct, more or less oblique, pressure will account for the observed phenomena. At the same time, he recognizes the inevitable complexity of the stresses involved.

This conclusion may have an important bearing on the subject of larger rock-faults. At the Washington meeting of February, 1882, I presented a paper on Hoefer's Method of Determining Faults in Mineral Veins,[9] based upon the author's

[9] *Trans.*, x., 456 (1881–82).

essay, which appeared in volume xxix. of the Austrian *Zeitschrift*. The peculiarity of Professor Hoefer's method is, that it provides for the case of a relative movement of the two walls of a fault which is not rectilinear, but to some extent rotatory; that is, in which a partial revolution of the mass on one side of the fault has taken place around an axis normal to the plane of the fault-fissure. The evidence of such a motion is found in changes of dip and strike, produced by the fault, in the fissure faulted. I wrote to Professor Hoefer at that time, telling him that this phenomenon had not been recognized in our mining-districts to any great extent, and asking whether such movements, distinct from rectilinear ones, had been frequently observed by him. His reply was:

"Circular movements, combined with movements in straight lines, are very frequent in our faults; in fact, I do not doubt at all that a continued careful study will show them to be the rule. Whether simple revolutions often occur, is very difficult to decide from the observations thus far available." [10]

It is my present belief that the circular movements have been, as a rule, not only accompanied by straight-line movements, but that the latter have been predominant; and it seems to me most reasonable to suppose that rotation has been caused, not by the direction of the forces which caused rupture, but by the resistance encountered in the course of a rectilinear slide. It is, indeed, almost inevitable that such a movement would not be wholly rectilinear, but that the mass would be turned more or less around points of greater friction. In other words, the seeming effects of torsion might be produced after the occurrence of a rupture in which torsion had taken no part.

In this view the causes of rupture on the large scale would be entirely analogous to those observed on the small scale in joints. This is a familiar principle to those who have worked upon rocks with the microscope, or have studied in hand-specimens the features exhibited in rock-masses. We find in all sizes the phenomena of faults, contortions, cavities, segregations, etc.; and we are almost irresistibly led to the conclusion that the microscopic is but the image of the macroscopic, and *vice versa*. But, in accordance with this principle, it may be (indeed, it ought to be) true that the small ruptures are some-

[10] For a single and uncertain instance of possibly simple circular movement, adduced by Professor Hoefer, see my paper above cited, p. 463.

times produced, as are larger faults, by tensile stress. In fact, I think such minute tension-ruptures are frequently to be observed, but they do not generally, if, indeed, they ever do, exhibit the smoothness and regularity of joints.

MR. BECKER: I may remark that faults supposed to be produced by torsion are said to be so common in certain French mining-districts that the miners have a special name for them. They call them hinge-faults, which is, I think, a very good name.

The term "joint" I regard as used simply for convenience to designate those partings in rocks on which the throw is not apparent without close observation. Excepting in the amount of throw, they are not distinguishable from the paraclastic ruptures on which mineral veins form. Even on joints ores sometimes occur, *e.g.*, the "paints" of the quicksilver-mines. Joints also pass over into cleavage. This structure sometimes consists of closely-grouped joints of microscopic throw, and sometimes of mere deformation not carried quite far enough to induce rupture. Cleavage and faulting are equally orogenic disturbances.

C. R. BOYD, Wytheville, Va.: In examining a silver-mining property at Conrad Hill, 6 miles southeast of Lexington, Davidson county, N. C., several years ago, I found two series of fissures crossing each other, one set being mainly filled with carbonate of iron and magnesia, the other with iron and copper pyrites, carrying gold and silver. The individual fissures of each series were not more than 15 or 20 ft. apart. The carbonate veins had a north-and-south strike, and a dip of 30° west. The pyrites veins ran east of north and west of south, dipping 40° west of north. The angle between the two series was about the same as that which the mountain ranges of that section make with the true meridian. That both series could have resulted from simple tangential strains or thrusts would be difficult to prove, and that they could both be fissures of contraction I hardly believe. Possibly torsion may have caused them; but it is more probable, in my judgment, that they resulted from disturbances proceeding from separate *foci*, and not necessarily simultaneous.

MR. BECKER: The angle depends on the amount of distortion which has preceded rupture. If a substance is brittle, like glass or cast-iron, and yields to rupture before it has been deformed to any considerable extent, the fissures will cross at right angles. If, on the other hand, the character of the mass or its confined position (as is often the case with rocks) prevents rupture from occurring until deformation has reached an extreme limit, the angle between the direction of the force and that of fracture may be even 50° or 60°, and large angles seem always to mean great preliminary deformation.

The most usual conditions of rock-fracture involve the simultaneous formation of two sets of fissures; but when the resistances in all directions perpendicular to the line of force are substantially uniform, four sets of ruptures may form, each being at 45° or more to the line of force, and all four sets will be slickensided. A single system of parallel faults involves the action of a "rotational" stress (which is, of course, utterly different from a torsional stress); and a solitary fault arises as an extreme, and in my experience rare, case of a rotational stress. I am inclined to believe that when two or three or four systems of joints or fissures intersect a rock-mass they were, as a rule, formed simultaneously. When a rock is once shattered a fresh force meets, in general, with very unequal resistance in different directions, and will cause disturbance on the old fissures or brecciate the whole mass rather than induce a new, regular system of intersecting partings.

No. 5.

The Allotropism of Gold.

BY HENRY LOUIS, LONDON, ENGLAND.

(Virginia Beach Meeting, February, 1894. *Trans.*, xxiv., 182.)

It can scarcely be considered a matter of doubt, in the present state of our knowledge, that the existence of, at any rate, two well-marked allotropic modifications of gold can be recognized, namely (*a*), the ordinary, yellow variety, and (*b*) the red, brown or purple, non-lustrous, amorphous variety.

There are, indeed, not wanting indications that still other allotropic forms may be capable of existing. It is, for instance, possible that the green colors of gold obtained under certain conditions, or the black powder produced when the alloy of gold with potassium is decomposed by water, may represent further allotropic modifications, although this proposition is open to doubt. It can scarcely be pretended that the two first-named varieties have been absolutely isolated, yet it is, perhaps, quite permissible to speak of the ordinary and the amorphous modifications as having a proved existence.

Ordinary gold is sometimes found crystallized in nature, although never in a state of purity. When gold is melted and cooled slowly, its surface shows crystalline markings, and the fact that it is capable of crystallizing in the cubic system may be looked upon as established. When gold is produced by precipitation, the form which it assumes is dependent on the conditions of precipitation. G. Rose[1] says that gold precipitated by ferrous sulphate from very dilute solutions is so finely divided that no regular form can be recognized, but in more concentrated solutions the precipitate consists of minute cubes. When oxalic acid is used as a precipitant, the gold is coarser and forms octahedral crystals. J. Thomsen[2] has obtained similar results. Working with dilute and with highly-dilute

[1] *Poggendorff's Annalen der Physik und Chemie*, vol. lxxiii., p. 8 (1848).

[2] *Journal für praktische Chemie*, vol. xiii., p. 348.

solutions, I have myself been quite unable to recognize any crystalline structure, even under the highest powers of the microscope; nor did there seem to be even any tendency of the particles to group themselves into arborescent forms, such as might indicate incipient crystallization. Precipitates from solutions containing between 0.0001 and 10 per cent. of gold gave no indications of crystallization, even when magnified 800 diameters.

Thomsen (*loc. cit.*) has also pointed out that the physical characters of precipitated gold differ according as it has been precipitated from solutions of its chloride or its bromide. He also found that these different forms possessed different degrees of thermic energy, and hence deduced a strong argument in favor of their being allotropic varieties.

The specific gravities of various forms of gold differ considerably. G. Rose (*loc. cit.*) found that fused gold had a density of 19.3336 after it had been compressed in a coining-press, it being a little lower before this mechanical treatment. The density of precipitated gold thrown down by ferrous sulphate he found to vary from 19.5419 to 20.6882, the highest figures being obtained from extremely-dilute solutions, the precipitate from which showed no trace of crystalline form; when precipitated by oxalic acid its specific gravity was 19.4791. When such amorphous gold was struck in the coining-press, its density became *reduced* to 18.0194. I have found that the density of gold left on dissolving out various metals alloyed with it, when the gold remains behind in a brown, amorphous, lusterless condition, varies between 20.3 and 19.5.[3]

It is only fair to notice that Rose did not ascribe the differences in the densities of the different forms of gold to allotropism, but has suggested another explanation, which is hardly, to my mind, a sufficient one. It is probably safe to assume that there are two modifications of gold—one a light one, of density 19.3 or thereabouts, and the other a heavy one, the density of which approaches 20.7—while various combinations of these extreme forms are capable of occurring.

In this connection the curious divergencies in the densities of specimens of native gold, from different localities but of

[3] See note by the writer, *Trans.*, xxii., 117 (1893).

about the same composition, may also be referred to; allotropism may, at any rate, be suggested as a possible explanation of them. There are thus sufficiently well marked differences in physical characteristics to support the hypothesis of allotropism.

As regards chemical properties, Thomsen has also pointed out that when amorphous, pulverulent gold is acted on by chlorine or bromine, aurylic compounds (Au_2Cl_4 or Au_2Br_4) are produced; whereas, these same substances produce auric compounds ($AuCl_3$ or $AuBr_3$) with ordinary gold.

I have found another point of difference, of far greater practical importance, in the behavior of these modifications towards mercury. Ordinary gold, of course, amalgamates readily, as is well known. I have found that gold precipitated from highly-dilute solutions by ferrous sulphate is not attacked at all by mercury when freshly precipitated, and only slightly after drying on an air-bath. Near the boiling-point of mercury, partial amalgamation took place, but it was by no means complete. Mercury containing a large amount of sodium amalgam was equally without effect on the dry gold, although it readily and completely amalgamated it when moist. In these observations I seem to have been partly anticipated by Ludwig Knaffl,[4] who, however, appeared to attach little importance to his observations. In a brief note on the preparation of certain amalgams of gold, he says:

"Gold precipitated by green vitriol or mercurous nitrate is not suitable for amalgamation, as it is too finely divided and always *floats on the surface of the mercury*[5] as a black powder, whether heated mercury be poured upon heated gold or *vice versa*. I examined this floating black powder, and found it to contain gold and mercury. . . . Gold precipitated either by means of arsenious acid or by boiling a solution of the chloride in amylic alcohol, when it separates out in small, lustrous octahedra, is best suited for amalgamation."

It may also be added that the purple of Cassius, which probably contains an allotropic modification of gold, is not attacked by mercury. The black pulverulent form of gold resulting from the decomposition of the potassium-gold alloy likewise resists amalgamation. On the other hand, the coherent gold

[4] *Dingler's Polytechnisches Journal*, vol. clxviii., p. 282 (1863).

[5] The italics are mine.—H. L.

sponge left on dissolving out the alloying metal from a gold-alloy amalgamates fairly readily, as does also the coherent pale-brown powder produced by precipitating with sulphurous acid a strong solution of auric chloride.

All forms of gold are converted into the ordinary yellow, lustrous variety by the action of heat. A very high temperature is not required, but the exact point has not yet been determined; it is certainly well above 200° C., but probably under 600° C.[6] Powerful mechanical action, such as percussion, friction, or compression, has the same effect.

I do not pretend that the above data form anything like a complete chain of evidence proving irrefragibly the allotropism of gold, or that our knowledge of this subject is precise or definite; yet I venture to think that the facts do warrant us in looking upon the following deductions as probably correct:

1. Gold is capable of existing in allotropic modifications.

2. One of these modifications is capable of amalgamation only with great difficulty, if at all.

3. This modification is capable of being produced and of subsisting under conditions that may reasonably be supposed to exist in nature when gold is deposited in reefs.

Whatever may have been the nature of the solution by means of which gold has been introduced into the deposits in which we find it, whether as a soluble haloid salt, as is generally supposed, or as an alkaline aurate, as I venture to suggest,[7] it must have been precipitated from such solution in various ways and under varying conditions. We have but few indications of the cause of this precipitation, but it is reasonable to conjecture that such reagents as ferrous sulphate or sulphurous acid, both resulting, perhaps, from the slow oxidation of iron pyrites, may have found their way, in solution, into the fissures within which the gold-solution was circulating, and may thus have caused the deposition of gold within the reefs. Now, if the gold, thus deposited from highly-dilute solutions, happened never to be exposed to a particularly high temperature, or to violent mechanical action, the conditions would be favorable

[6] I am at present engaged in investigating this point, and hope to publish shortly the result of my research.—H. L.

[7] On the Mode of Occurrence of Gold, *Mineralogical Magazine*, vol. x., No. 47, p. 241.

to the production of that allotropic modification of gold which is indifferent to the action of mercury. In other words, under the above conditions, an auriferous deposit will have been produced in which a greater or smaller part, or perhaps even the whole, of the gold is what gold-miners term "rusty." I have little doubt that the "rustiness" of gold is in different cases due to widely-different causes—that, in fact, there is more than one kind of "rustiness;" but I venture to think, also, that there is sufficient evidence to warrant us in classing allotropism among such causes of "rustiness." If this is correct, I need hardly point out either the great practical value or the application of this deduction. The gold which is thus allotropically indifferent to mercury is in a condition in which it is readily attacked by such reagents as chlorine and potassic cyanide. I have pointed out long ago that the gold of the Witwatersrand deposits of the Transvaal was probably deposited *in situ* under some such conditions as I have sketched above, and it is now notorious that a large proportion of the gold in them is not attacked by mercury, but readily by potassic cyanide solution. Again, in some cases it may be economically feasible to convert the non-amalgamable modification of gold into the common amalgamable variety by heating the ore to a moderate temperature, or the same end may be attained by mechanical means. In any case, the only really sound method of preventing losses of gold in the process of gold-extraction is that of ascertaining, in the first place, the ultimate causes of such loss; and I venture to hope that it will be found that among such causes, the one here treated of—namely, allotropism of gold—will be found worthy of more consideration than it has hitherto received from scientific gold-miners.

No. 6.

The Superficial Alteration of Ore-Deposits.

BY R. A. F. PENROSE, JR., U. S. GEOLOGICAL SURVEY.

(Reprinted from *The Journal of Geology*, vol. ii., No. 3, Apr.–May, 1894.)

I. INTRODUCTION.

THE superficial alteration of ore-deposits is a recognized principle of geology, in the same way as is the superficial alteration of any of the common rocks. Its importance in some classes of ore-deposits is also well understood, as in many precious-metal deposits; while in other classes, its importance has been proved in individual cases, as in the Lake Superior iron-deposits. The causes and effects of superficial alteration in many classes of deposits, however, are not so generally understood; and it is the object of the present paper to show that such changes almost invariably give rise to exceedingly important chemical and physical phenomena, while in many deposits, the question as to whether they can or cannot be profitably worked depends largely on the extent and character of this alteration.

The various treatises on ore-deposits published in the United States and Europe make frequent mention of superficial alteration, but have not treated the subject fully. As early as 1854, however, before which time but little accurate information was had on the geologic nature of ore-deposits, Prof. J. D. Whitney in his classic volume, *The Metallic Wealth of the United States*, describes the alteration-products, or gossans, in certain deposits and mentions others. On the more purely chemical side of the question, the work of Bischof, Daubrée, Roth, Rose, Hunt, Breithaupt, Blum, Julien, Deville, Debray, Volger, Moissan, Fremy, Lévy, Fouqué, and others has afforded much valuable information and many useful suggestions. The chemical principles brought out by these various authors have been applied, to a certain extent, to the solution of the phenomena of

the origin of ore-deposits, but have not as yet been applied to anything like their possible extent to the solution of the phenomena of the alteration of ore-deposits.

II. General Features.

Scope of the Subject.

The modern idea of ore-deposits teaches that formations of this kind represent a process of concentration of mineral matter, either by chemical or physical means; in other words, that they are unusual localizations of certain minerals which are often found disseminated in smaller quantities in many common rocks, and that they differ from the same minerals situated in other conditions, only in their degree of concentration. These concentrations may take place at different times in the history of the rocks in which the deposits occur. If they occur in sedimentary rocks, they may sometimes be formed during the deposition of the rocks with which they are associated, as in the cases of placer-gold, stream-tin, and sometimes of other ores; while if they occur in igneous rocks, they may sometimes be the result of concentration by differentiation from fused magmas.[1] More usually, however, ore-deposits are a result of a concentration after the formation of the inclosing rock, whether the latter be of sedimentary or of igneous origin. The mineral matter represented in this concentration may be derived from the inclosing rocks or closely-adjacent rocks, as in the case of many, if not most, iron-ore deposits; or it may be derived from more distant sources, often from greater or less depths, as in some of the precious-metal deposits. Occasionally, both these sources may be drawn on for mineral matter in one deposit. In this subject of the original source of an ore, we enter a field concerning which there has been much dispute of late years between the advocates of the lateral-secretion theory and those who favor the idea of a deep-seated source for many ore-deposits. It is not, however, the purpose of the present paper to enter into this discussion, and the following

[1] This has been shown by J. H. L. Vogt (*Zeitschrift für praktische Geologie*, Jan., 1893) to be true of certain titaniferous iron-ores and other deposits in the eruptive rocks of Norway. It may also be true of certain titaniferous iron-ores in the United States.

remarks are confined to what happens in the superficial parts of ore-deposits, and to a less extent of allied formations, after the materials forming them have been brought into their present, or approximately their present, positions.

Relation of Alteration in Ore-Deposits and in Country-Rocks.

Ore-deposits are generally more or less changed in their upper parts by atmospheric influences, so that very rarely do the same mineralogical and physical features that are found in these parts continue to very great depths. In considering this superficial alteration, we discuss a subject analogous to the secular decay of rocks. The latter, however, involves usually but a limited number of common rock-forming minerals, while the secular decay of ore-deposits involves a great variety of minerals, not only the oxides, carbonates, and silicates common in most rocks, but also sulphides, arsenides, tellurides, selenides, antimonides, chlorides, bromides, iodides, fluorides, sulphates, phosphates, tungstates, molybdates, and numerous other classes of minerals, many of which, under surface-influences, give rise to intricate chemical changes. In discussing the subject of the superficial alteration of ore-deposits, therefore, we treat a similar, but much less understood, subject than the superficial alteration of rocks.

Technical Names of Alteration-Products.

The altered surface-outcrop of ore-deposits is known by various names in different regions. Among the Cornish miners of England it is known as *gossan*, a name which has also been adopted into American mining nomenclature, though other special names are given in special classes of deposits. In France it is known as *chapeau de fer;* in Germany as *eisener Hut;* among the Spanish Americans as *pacos* or *colorados.* As almost all deposits contain more or less iron-minerals, the outcrops are usually stained brown from their oxidation, and hence the reference to iron in the French and German names. Sometimes, however, the outcrops are stained black by the oxidation of manganese carbonate or silicate, or green by copper-minerals, or other colors by the formation of other compounds.

Agents of Alteration.

The superficial alteration of ore-deposits, as of any rock, results from a combination of mechanical and chemical disintegration, brought about by the combined action of the atmosphere, surface-waters, changes in temperature, and the various organic and inorganic materials contained in the air and water. In nature, we never deal with perfectly pure water, but different waters contain different ingredients derived from the air and from the different materials with which they come in contact. Among the most important of these ingredients are oxygen, numerous organic acids like carbonic, oxalic, malic, citric, formic, propionic, butyric, acetic acids, etc., certain inorganic acids, such as sulphuric, nitric, hydrochloric, hydrobromic, etc. Some of the acids mentioned occasionally occur in the free state, but most of them are generally combined with some of the bases present, such as the alkalies, lime, magnesia, iron, alumina, etc. These various ingredients, of course, are not all contained in the same waters, but are found in various associations in different waters. The organic acids mentioned represent various stages of oxidation of materials from organic matter, but they all eventually, if allowed to become completely oxidized, pass into carbonic acid; while if they are in combination with different bases, these salts are eventually converted to carbonates.

Method and Chemical Effects of Alteration.

Surface-waters thus charged with various chemical ingredients percolate down into ore-deposits, and there meet various materials which are even less stable under their influence than most of the common rocks. The alteration, therefore, is comparatively rapid, and, though only superficial, generally extends to much greater depths than in the surrounding country-rock. From a chemical stand-point, the first effect of this superficial influence is usually the oxidation, or hydration, or both, of certain ingredients, followed generally by the formation of other chemical combinations and by the leaching of certain materials. In the formation of these other chemical combinations, however, the base usually remains the same, and the alteration consists generally in a change of the materials associated with the base, that is, in the acidic portion of the mineral or the

part that represents the acidic portion. Thus, iron sulphides are oxidized to iron sulphate, and then this is converted by further oxidation and by hydration to the hydrous sesquioxide. Copper sulphides may be oxidized to copper sulphate; and from the sulphate, by the agency of materials in surface-waters, may be formed copper carbonates, haloid compounds, silicates, oxides, and even metallic copper; while from some of these, still other compounds may be produced. Similar reactions occur in many lead-, zinc-, silver-, gold-, and other deposits.

Occasionally, chemical changes may occur without previous oxidation, and sometimes, though rarely, surface-influences under peculiar conditions may have a reducing effect, as in the formation of iron pyrites and copper pyrites from the sulphates of iron and copper, or in the formation of native copper by the action of a ferrous salt on certain copper salts, or in the formation of native silver in surface-outcrops. In many of such cases, however, the chemical action is primarily one of partial oxidation, and the reducing action follows as the effect of one of the partly-oxidized compounds on the other, as in the case of copper just mentioned. In deposits such as gypsum, a reduction, due sometimes to superficial influences, is seen in the occasional formation of sulphur from gypsum.

An important chemical effect of surface-influences is the removal in solution of certain ingredients of the ore-deposit which are soluble in surface-waters; as the removal of the calcite gangue of many silver- and other deposits; the oxidation and removal of the sulphur in various silver-, lead-, zinc-, copper-, and other deposits; the oxidation and removal of both the iron and sulphur of iron pyrites in auriferous quartz veins; the removal of silica from certain iron-deposits, such as those in the Lake Superior region, etc. Probably many phosphate-deposits are formed by the superficial leaching of carbonate of lime from calcareous beds, and the corresponding concentration of phosphate of lime once finely disseminated in the same beds.

Another chemical effect of superficial alteration is seen in the occasional formation of mineral deposits of importance by certain materials carried from outside sources and deposited in a rock of otherwise no commercial value. Thus certain phosphate-deposits of the South Pacific ocean, the West Indies,

and possibly of Florida, are formed by the leaching of soluble phosphates from guano, their transportation down into underlying limestone or coral reefs, and the precipitation of the phosphoric acid as tribasic phosphate of lime, which, being almost insoluble, arrests further escape of the phosphatic materials.

Again, another chemical effect is seen in the incrustations, and even extensive beds, of saline materials, like borax, niter, and the various alkaline salts of the Western arid regions, formed by precipitation from water rising by capillary action through the soil, becoming evaporated on the surface and depositing the saline materials which it has dissolved from below. Many saline deposits are formed by the simple evaporation of surface-waters, such as lakes, seas, etc., but certain deposits undergo only an initial concentration in this way, and are laid down with clay, sand, and gravel, while further concentration is due to this capillary action. In the case of niter, indeed, the saline material is very often, if not generally, formed in soils or guano-beds and undergoes its first concentration by this capillary action.

In the various chemical changes mentioned above, the class of salts that remains, whether oxides, carbonates, haloid compounds, etc., varies with the nature of the bases affected. Thus, iron sulphides and copper sulphides are both oxidized and form sulphates. But here the similarity of their behavior ends, for the iron sulphate probably passes then into a basic sulphate and then into a hydrous sesquioxide, while the copper sulphate takes up carbonic dioxide and water and forms basic carbonates. The iron sulphate might, under certain conditions, form a carbonate in a similar manner, but this compound would be very unstable under the conditions existing in the alteration of sulphide deposits and would quickly go into the form of the hydrous sesquioxide, while the carbonate of copper is stable under existing conditions and remains.

In the same way, if silver sulphide and iron sulphide are both oxidized and then affected by waters carrying common salt or other chlorides in solution, the silver is converted to chloride, which is insoluble and remains; while the chlorides of iron are much less liable to be formed, as they are soluble, and some of them unstable, compounds, and even if they were

formed, they would be leached out or oxidized. Hence, though chloride of silver is a common product of alteration in silver-deposits, chloride of iron is never found, at least to any extent, as a product of alteration of iron-deposits.

Again, it is frequently found that unaltered auriferous iron pyrites contains a certain amount of silver, while the altered part often carries almost none. In such cases, the gold has remained stable during the alteration, while the silver, in the absence of a chloride or other reagents to convert it to an insoluble compound, has been dissolved and carried away in solution by the acid materials generated during alteration.

Hence, the materials in surface-waters affect different bases differently, and, therefore, there is a great difference in the classes of salts formed by the same surface-waters on the ores of different metals. In the same deposit there may be formed an oxide of one metal, a carbonate of another, a chloride of another, etc. In fact, in some of the silver-deposits of southern New Mexico, there can be found hydrous sesquioxide of iron formed from iron sulphide, carbonates of copper formed from copper sulphides, and chloride of silver formed probably from silver sulphides, and yet in all probability the same surface-waters produced all these changes practically simultaneously.

As a result of these various changes, certain materials are sometimes leached from the upper parts of ore-deposits, which have become porous by alteration, and carried down to the less pervious unaltered parts. Here they are precipitated by meeting other solutions or in other ways, and hence the richest bodies of ore in a deposit often occur between the overlying altered part and the underlying unaltered part. This is not always the case, but it is true of some copper-, silver-, iron-, and other deposits.

Physical Effects of Alteration.

From a physical stand-point, the effect of superficial alteration is generally to make the deposit more open and porous, to cause it to shrink, and, in some cases, to convert it to a loose material of the consistency of sand and clay. In some cases, however, especially where considerable hydration goes on, an expansion may be caused. This is well seen in the formation of gypsum by the hydration of anhydrite, often causing an ex-

pansion sufficient to brecciate and fold the associated rocks,[2] and amounting to about 33 per cent. of the original material.[3] In the conversion of carbonate of iron to the hydrous sesquioxide of iron, or limonite, it has been found[4] that there is a contraction of 19.5 per cent., giving the deposit the loose porous structure characteristic of limonite and forming the familiar limonite geodes.[5] In this case carbon dioxide has been removed from the iron, but oxygen and water have been added. A porosity is also produced by the removal of certain ingredients in an ore-deposit without the addition of others, as in the oxidation and leaching of iron pyrites in veins of auriferous quartz, leaving a loose, porous, spongy quartz mass.

Surface-decomposition has also, in many places, not only affected the ore-deposit itself, but also the country-rock in the immediate vicinity, and has converted it into a loose material of a sandy or clayey consistency, as at Iron Mountain, Mo., in the Batesville manganese-region of Arkansas and in other localities described beyond. In the iron- and manganese-deposits of the Cambrian and Lower Silurian rocks in the Appalachian region, the limestones and shales, which once inclosed the ore-bodies, have often been converted to clay in the same way as in the Batesville region; and, in fact, the common mode of occurrence of these deposits is as residual clays carrying irregular bodies and nodules of ore.

This decay of the country-rock in immediate association with ore-deposits, is generally more extensive than in similar rocks not associated with such deposits, and, therefore, requires further explanation than the simple action of ordinary surface-waters. The explanation is, doubtless, in many cases, that the rock has decayed under the influence of the same waters that originally concentrated the ore; and as these waters differed from most waters in character and in the materials they held in solution, they often had an abnormal effect. Moreover, when subsequently the ore-body is affected by surface-influ-

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[2] Elie de Beaumont, *Explic. Carte géologique de France*, vol. ii., p. 89. R. A. F. Penrose, Jr., *Arkansas Geological Survey*, vol. i., pp. 535 to 538 (1890).

[3] A. Geikie, *Text Book of Geology*, 3d ed., p. 345 (1893).

[4] T. Sterry Hunt, *Mineral Physiology and Physiography*, p. 262 (1889).

[5] R. A. F. Penrose, Jr., The Tertiary Iron Ores of Arkansas and Texas, *Bulletin of the Geological Society of America*, vol. iii., pp. 44 to 50 (1891).

ences, sulphuric acid is liberated from sulphides and carbonic acid from carbonates, as well as other acids from other minerals, and all these materials have an active effect on most rocks. Moreover, the porous nature of many ore-deposits, after they have been altered on the surface, allows a freer percolation of surface-waters than elsewhere in the same country-rock, and, hence, a correspondingly greater decay.

Another physical effect of surface-influences on ore-deposits is seen in certain forms of brecciation due to physical or chemical causes, such as expansion by hydration, etc. Such brecciation, however, has usually occurred in the country-rock before the concentration of the ore-deposit; in fact, its existence, by offering favorable conditions for deposition, has often been the cause of the formation of the ore-deposit in a given place. Though brecciation, therefore, is very important as a factor in the concentration of ore-deposits, it does not belong, to any large extent, in a discussion of the surface-alteration of ore-deposits after their formation, and, therefore, it will not be treated further in this paper.

Depth of Alteration.

Having thus discussed briefly the means by which superficial alteration in ore-deposits is produced, and the results of this alteration, the next feature to be taken up is the depth to which it extends. As already shown, the alteration is primarily one of oxidation and generally of hydration; and, though either may occur without the other, they both very often occur together. When surface-waters percolate into the rock, their influence is more active near the surface, because they carry large quantities of oxygen, and because the oxygen of the air itself also has some influence. As they sink deeper, the effect of the oxygen of the air becomes less active, and the oxygen dissolved in the water is consumed in oxidizing various materials which it meets on the way, until finally most of the oxygen is lost and active oxidation ceases. Theoretically, this oxidizing action may extend down as far as, and sometimes below, the level of the drainage of the surrounding country, which is called also the zone of permanent saturation. Above that level, there is a constant circulation of water from the surface downward, thus affording means of active oxidation; but when

the water reaches that level, not only has most of the oxygen contained in solution generally been used up, but also the circulation of the water is much more sluggish, so that oxidation is less active.[6]

The process of hydration, when the materials affected do not require oxidation before they can become hydrated, may extend down indefinitely below the limit of oxidation; but when oxidation is necessary before hydration is possible, the latter process of course can extend no deeper than oxidation. Thus the silicate of aluminum in feldspar may become hydrated and form kaolin without the intervention of oxygen. This is brought about by the action of carbonic acid and water, which react on the feldspar and form alkaline carbonates, kaolin, and free or hydrous silica. Theoretically, therefore, kaolinization ought to go on to any depth that can be reached by water and its almost universal accompaniment, carbonic acid. In this case, however, the base in question is already in its peroxide condition ($Al_2 O_3$); but when a base is not in this condition, it frequently requires oxidation previous to hydration. Thus sulphide of iron does not become hydrated until it is peroxidized, and this mineral, therefore, requires oxidation previous to hydration.[7]

The various materials other than oxygen in surface-waters have a very important effect on the mineral matter with which they come in contact, and their action sometimes takes place before that of oxidation, though it often requires at least a partial previous oxidation. The effect is both to form new chemical compounds with the materials involved, and to dissolve and bodily remove certain materials. As with oxygen, however, so with these other agents of alteration, they are more active above the drainage-level of the country than below it, and an additional reason for this is that many of the materials affected require a primary oxidation before they enter into other chemical combinations. Thus sulphide of lead is oxidized to

[6] It is possible that the oxidation near the surface is due largely to free oxygen in the waters, while, when this becomes exhausted at a depth, the oxidation may be due to the abstraction by mineral matter of the oxygen in combination with materials in solution.

[7] For a full discussion of this subject see H. Rose, Ueber den Einfluss des Wassers bei chemischen Zersetzungen, *Poggendorff's Annalen der Physik und Chemie*, vol. lxxxii. (1851) *et seq.*

sulphate of lead before it can take up carbonic acid and form carbonate of lead; while on the other hand, carbonate of lime can be converted to sulphate of lime (gypsum) by the action of sulphuric acid or certain sulphates without any change in the degree of oxidation of the lime.

It will thus be seen that in going from the surface downward, we pass from a zone of active oxidation into a zone in which oxidation practically ceases. Below the level of permanent saturation, the waters may sometimes gradually sink to very great depths, even deep enough to become intensely heated and possibly dissociated. Such waters may have a very important effect in the formation of ore-bodies, though in a manner quite different from their action on the surface. The present discussion, however, relates not to this, but to only superficial influences.

Though theoretically, therefore, alteration of one kind or another may extend down to, and in some cases much below, the level of permanent saturation, and if given sufficient time would actually go to such depths; yet in many, if not most, cases it has not yet reached that level. The actual depth to which alteration does extend varies with the topographic conditions of the region, the chemical nature and the porosity of the deposits affected, the character of the climate, and other minor conditions.

The topography of a region affects the depth of alteration because it is one of the principal features in determining the depth of permanent saturation. The chemical nature of the deposit affects the depth of alteration because on this depends the degree of resistance it will offer to the chemical effects of percolating waters. The porosity of the deposit affects the depth of alteration because, in deposits of similar kind but of different porosity, the more porous will be more accessible to surface-influences, and will, therefore, be more affected, in a given time, than the less porous deposit.

The climatic conditions, such as the amount and manner of occurrence of rain-fall and other forms of atmospheric moisture, and the rate and degree of variation in temperature, have a large influence on superficial alteration. On the amount of rain-fall and other forms of atmospheric moisture depends the amount of moisture available as an agent of alteration; while on their

mode of precipitation depends, other things being equal, the amount of water which would sink into the deposit, thus effecting alteration, and the amount that would immediately run off the surface or be evaporated and thus have but little altering effect. The rate and degree of variation in temperature affect the amount of breaking in the rock by expansion and contraction, and, therefore, the accessibility of the rock to surface-influences. The character of the climate also influences, to a certain extent, the nature and amount of vegetation, and from the vegetation are obtained many organic acids which assist the action of surface-waters. In other ways, also, such as in the generation of nitric acid in the atmosphere, the character of the climate influences the agents of alteration.

As a result of all these influences, surface-alteration is found to extend in different ore-deposits to depths varying from only a few inches, or in fact only a fraction of an inch, to several hundred and even a thousand or more feet. In glaciated regions the products of decay have often been swept away by glacial action, and the time which has elapsed since then has not been sufficient for alteration to have extended to any great depths; while in regions of moist climates, the erosion sometimes, though not always, keeps pace with the alteration, so that the depth of the change is shallow. In those regions, however, which have not been recently glaciated and which have dry or only moderately moist climates, so that erosion is slight; or in places which have moist climates, but which, on account of their topography, are not subjected to very active erosion, the products of alteration collect, and the changes are traceable downward often to great depths.

In the copper-regions of Michigan, the deposits have been exposed to glaciation, and are still exposed to the active effects of erosion in a moist climate, so that here, though the native copper of the region is a material very easily affected by surface-alteration, yet the only change observable is a slight stain of copper carbonate or oxide on the surface of some of the native copper, and even this is not always present. On the other hand, in the arid region of the West, most of which has not been recently glaciated and which has an exceedingly dry climate, the residual products of alteration have accumulated to great thicknesses. This region, however, had once a much

more moist climate than now, and some of the alteration may have occurred then. Many of the Arizona copper-deposits in this region originally contained their copper in the form of copper pyrites, which, under similar conditions, is probably more resistant to surface-alteration than the native copper of Michigan, and yet it has been changed to various other copper-minerals for depths often reaching from 100 to over 700 ft. In Chile some of the copper sulphide deposits are said to have been altered to a depth of 1,500 ft., but it is very rare that much alteration extends in any ore-deposits to greater depths than this. In the more moist climate of Tasmania, the results of alteration are also very marked.

The depth of alteration of ore-deposits in unglaciated regions in the United States varies from a few feet to over 1,000 ft. In the Appalachian region, many of the deposits of auriferous quartz, iron pyrites, copper pyrites, etc., are altered to depths varying from less than 1 to 100 ft. or more. Many of the Clinton iron-ore deposits are altered to still greater depths. The depth of alteration in these Appalachian deposits is usually much greater, other things being equal, south of the limit of glaciation than north of it. In the silver-, lead-, gold-, and copper-deposits of the Rocky mountains and the Western arid region, such as at Butte City, Leadville, Central City, Cripple Creek, Silver City, Lake Valley, Eureka, Virginia City, Park City, the Cœur d'Alène district, and elsewhere, the alteration has reached depths ranging from 50 to 600 or 700 ft., and in some rare cases still more. At Granite Mountain, in Montana, signs of alteration are seen in the argentiferous quartz-deposits of that region, even at depths of 900 ft., though of course at such depths the alteration is slight as compared with that nearer the surface.

Complete alteration rarely extends to these greater depths, and usually parts of a deposit which have as yet escaped alteration appear comparatively near the surface. These are at first very few and may be entirely inclosed by altered products, but with increased depth they become more numerous and continuous, until they predominate over the altered products, and finally, when the limit of alteration is reached, they entirely replace them. The planes of contact between an ore-deposit and the country-rock, that is, the walls, afford, when well

defined, easy passages for the downward percolation of surface-waters, and therefore alteration frequently continues down along these lines for considerable distances after the limit of alteration in the main part of a deposit has been reached. Any other possible channels, such as the planes of contact of different minerals in banded deposits or the series of drusy cavities often found in the central parts of ore-deposits, may act in the same way as passages for water. Hence the not infrequent abundance of alteration-products, such as hydrous sesquioxide of iron, and native copper and silver, along the walls and elsewhere in certain deposits.

Classification of the Products of Alteration.

The products of superficial alteration may be divided into two general classes: (1) Those which occupy the same position as the materials from which they were derived, or are only slightly removed, and possess the same general environment. Thus the altered outcrops of auriferous quartz and iron pyrites, of argentiferous galena, of sulphides of copper and many other similar deposits, represent alteration-products occupying the same general position as the original sulphide ores; while the iron-ore bodies of the Lake Superior region represent alteration-products changed somewhat in position from that occupied originally, but yet in the same series of rocks and sometimes with somewhat similar environment. (2) In the second class are included those deposits which have been entirely removed from their original position and redeposited under totally different environments. Thus, placer gold-deposits, stream-tin, most of the deposits carrying platinum and the allied metals, magnetic and chromite sand, the gravels and sands carrying precious stones, and many other similar deposits, represent this class. They have been derived by the decay and erosion of veins, dikes, or country-rocks carrying the materials now concentrated in these fragmental deposits. The materials in their original environment may or may not have been sufficiently concentrated to serve as commercial sources of supply, but the fragmental deposits mentioned almost always represent a further concentration. This class of deposits is of great importance, but the present discussion relates more especially to the superficial alteration of deposits that remain *in situ*, and therefore

these will be treated more in detail than the other class (No. 2), though the latter will be mentioned as occasion requires.

III. Superficial Alteration in Different Deposits.

Alteration in Iron-Deposits.

It was once generally believed that most iron-deposits were the result of direct precipitation from aqueous solution, or in rarer cases, were igneous masses. It has long since been shown, however, that most workable iron-deposits are the result of a concentration subsequent to their deposition, while very few are due to a direct precipitation during the formation of sedimentary rocks, though some may be due to a process of differentiation in the cooling of eruptive magmas.[8] The original presence of the iron in sedimentary rocks was doubtless due to a direct precipitation during the formation of the inclosing rock, but it was then in a finely-disseminated condition, and it was only by being subsequently taken into solution again by percolating waters and concentrated, that it was converted into bodies of greater or less purity. Generally, though possibly not always, this process is superficial, and though it may extend to a depth of several hundred or even a thousand feet or more, it can be traced directly to surface-influences, and its effects are seen to decrease gradually with depth. Shaler,[9] in 1877, showed that some of the limonites of Kentucky, Ohio and elsewhere were concentrations of iron derived in solution from shales and other rocks and reprecipitated in underlying limestone.

Van Hise,[10] in 1889, showed that the iron-deposits of the Lake Superior region are concentrations of iron formerly disseminated in a siliceous rock containing carbonate of iron and other carbonates, and called by him cherty iron carbonate. This disseminated iron was taken into solution by surface-

[8] See foot-note [1], p. 111.

[9] N. S. Shaler, *Kentucky Geological Survey, Report of Progress*, vol. iii., New Series, p. 164 (1877).

[10] C. R. Van Hise, The Iron Ores of the Penokee-Gogebic Series of Michigan and Wisconsin, *American Journal of Science*, Third Series, vol. xxxvii., No. 217, pp. 32 to 47 (Jan., 1889); The Iron Ores of the Lake Superior Region, *Transactions of the Wisconsin Academy of Science*, vol. viii. (1891). For a fuller discussion by Van Hise on this subject see *Tenth Annual Report, U. S. Geological Survey*, Pt. I., pp. 409 to 422 (1888–89); *Monograph XIX, U. S. Geological Survey* (1892).

waters, carried down until its passage was obstructed or impeded by less pervious rocks, often dikes, and there precipitated by meeting with other solutions of a different nature. These other solutions contained oxygen, while the iron-bearing solutions had been largely robbed of their oxygen and had been freed from silica by the large amount of carbonic acid they contained. When, therefore, the two solutions met, the iron in solution was oxidized and precipitated; while the silica, in the spot where this precipitation occurred, was, on account of the dilution of the carbonated waters with the other waters, and through the agency of alkaline carbonates, dissolved and carried off, thus gradually increasing the amount of iron and removing the silica. By this theory, the iron is largely a replacement of the silica of the cherty iron carbonates, and has been derived from the parts of the strata exposed to superficial influences. The deposits are, therefore, of only superficial extent, though they may reach over 1,000 ft. below the surface, yet when they pass below the action of surface-influences the iron has not been concentrated, and they are of too low grade to be mined for iron-ore. The methods of local concentration proposed by Professor Van Hise for these Lake Superior iron-deposits are equally applicable to certain other iron-deposits, and are a most valuable addition to our knowledge of chemical geology. They also bring out in a most prominent manner, the fact that even rocks composed of materials like silica, which are very resistant to surface-influences, may, under proper conditions, be replaced on a large scale.

The iron-deposits of the Mesabi range, in Minnesota, which have lately been described by H. V. Winchell,[11] are supposed to have had a somewhat similar origin to that given for the Michigan and Wisconsin ores by Van Hise. Winchell believes that they are due to the concentration by surface-agencies of iron disseminated as oxides in a highly-siliceous rock, and that in this concentration the silica has been replaced by iron.

The red hematites of the Clinton horizon of the Upper Silurian in the Appalachian region have been at least partly formed by superficial concentration which extends to only limited depths.

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[11] *Twentieth Annual Report, Minnesota Geological Survey*, pp. 136 to 148 (1891).

The iron-deposits in other geologic horizons of the Appalachian valley, especially in the Cambrian, Lower Silurian, and Carboniferous rocks, are also often much changed by the action of surface-influences. Many of the deposits in the Cambrian and Lower Silurian can be clearly shown to be due to a superficial replacement of limestone, or even of more siliceous rocks like shales, by iron dissolved from ferruginous rocks in the neighborhood. In such cases, the iron in the original rock has been dissolved and carried off in carbonated surface-water, and re-precipitated in the other rocks, all these stages being directly due to surface-influences. Many of the carbonate iron-ores of the Carboniferous rocks are rendered not only of higher grade, but also more easy to treat, by the oxidation of the carbonate to the sesquioxide and the removal of the carbonic acid. Moreover, these carbonate ores often occur as nodules, "kidney ores," in shale, and, on the surface, this shale has been softened by atmospheric conditions, thus facilitating mining; while away from the surface, the shale becomes harder and makes mining more expensive.

Surface-influences on carbonate of iron have been made use of artificially in Styria, where a very hard spathic iron-ore has been mined and spread out on a hill-side for from 20 to 25 years. By this process the ore was oxidized and made more porous, and thus became very much more cheaply treated.[12]

At the celebrated Iron Mountain, in Missouri, a large part of the ore came from conglomerates composed largely of fragments of iron-ore, which had been weathered out of the pre-Cambrian rocks that had originally contained them. These conglomerates lie at the base of the Cambrian strata which overlie the pre-Cambrian rocks, and even in the latter rocks, where exposed, the original ore has been made much more easy to work by the decay of the inclosing material and its conversion to clay.

In the iron-region of eastern Texas, the limonite ores are often a result of the solution of iron from the superficial oxidation of iron pyrites, iron carbonate, and glauconite. Sometimes the sequel of this process is the downward passage of the solution to an underlying laminated clay, and the gradual re-

[12] Letter from Charles E. Smith, Philadelphia, Pa.

placement of this bed, forming a hard limonite,[13] which still preserves the laminated structure of the clay.

In Mexico certain hematite-deposits described by R. T. Hill[14] as occurring in Lower Cretaceous limestone at or near the contact with intrusive masses of diorite, and sometimes even in the diorite itself, may, as Hill suggests, be the result of superficial concentration from the limestone.

Very large deposits of hematite also occur in Grant county, N. M., at the contact of limestone and an eruptive. The origin of this ore is as yet somewhat obscure, but is probably due to a concentration after the original deposition of the iron.

The iron-deposits in the lakes of Sweden and Norway are most striking instances of a concentration of iron-ore due to surface-influences and going on at the present time. The iron is derived from the oxidation of the neighboring rocks, carried by carbonated surface-waters to the lakes, and there, by further oxidation and hydration, precipitated as hydrous sesquioxide (limonite). The iron-ore is dredged up and used, but the processes of nature gradually replace it, and, in the course of years, the lakes again accumulate a considerable thickness of ore.

Many other similar cases of superficial enrichment in iron-deposits might be mentioned, but the above are enough to illustrate the point in question, and it will be seen that, of the regions which are the active producers of iron-ore in this country, almost all, if not all, owe the existence, or at least the availability, of their large bodies of ore, to superficial concentration.

Alteration in Manganese-Deposits.

Manganese-deposits are affected by superficial influences in much the same way as iron-deposits. Many of the manganese-deposits in the Cambrian and Lower Silurian rocks of the Appalachian valley were concentrated in a manner somewhat

[13] R. A. F. Penrose, Jr., *First Annual Report, Geological Survey of Texas*, pp. 72 to 76, 79 to 81 (1890); also *Bulletin of the Geological Society of America*, vol. iii., pp. 47 to 50 (1891).

[14] *American Journal of Science*, Third Series, vol. xlv., No. 266, pp. 111 to 120 (Feb., 1893).

similar, though not always so, to the iron-deposits in the same regions.[15]

In the Batesville manganese-region of Arkansas, the ore originally occurred in irregular masses in Silurian limestone, but surface-decay has leached the carbonate of lime out of the limestone, leaving a red siliceous clay, which represents the less soluble part of the original rock. This clay now lies in hollows on the surface of the limestone and contains the masses of ore once disseminated through that rock. The removal of the carbonate of lime has concentrated the ore-masses in the clay, and has also rendered them more easily mined; in fact, the only manganese-ore that can now be profitably mined in this region is that in the residual clay.[16]

The frequent occurrence of deposits of bog manganese-ore in the areas of crystalline rocks, generally represents a concentration of manganese resulting from the oxidation of disseminated carbonate and silicate of manganese in the country-rock. This oxidation-product is taken into solution in surface-waters, and transported until subjected to such conditions that it is oxidized and precipitated as a hydrous oxide.

Alteration in Copper-Deposits.

In many copper-deposits superficial alteration has produced very remarkable chemical and economic results, and this is especially well seen in the copper sulphide deposits of Arizona, Chile and elsewhere. In Arizona the upper parts of the deposits are composed of brown or black ferruginous masses, with brilliantly colored oxidized copper-minerals, as cuprite, malachite, azurite, chrysocolla, etc.; while below, at depths varying from a few feet to several hundred feet, the deposits usually pass into a mixture of copper pyrites and iron pyrites, the latter usually being far in excess. Sometimes other copper sulphides occur, either mixed with copper pyrites or free from it, and they may or may not have been derived from it. Here the carbonates and some of the other alteration-minerals contain not only more copper than the unaltered copper pyrites, but they are also in a much more concentrated condition than

[15] R. A. F. Penrose, Jr., *Journal of Geology*, vol. i., No. 4, pp. 356 to 370 (1893).

[16] R. A. F. Penrose, Jr., Manganese: Its Uses, Ores, and Deposits, *Arkansas Geological Survey*, vol. i., pp. 166 to 209 (1890).

the sulphide which is disseminated through iron pyrites. The total amount of copper has not been increased, in fact it may be decreased by leaching, but it is in a more concentrated form, and therefore the ore obtained from these concentrations averages from 8 to 30 per cent. or more in copper, while the mixture of unoxidized copper pyrites and iron pyrites below averages only about 5 per cent. in copper. Moreover, the altered ores are much more cheaply treated than the unaltered ones, and are therefore still more desirable. It will thus be seen that the economic value of the deposits as a whole has been greatly increased.

In the surface-alteration of these deposits, the copper sulphides have first been converted to copper sulphate and then, by the action of surface-waters and the materials contained in solution in them, they pass into the forms of copper carbonates, oxides, silicates, and occasionally to the chlorides and bromides, and sometimes to native copper. The iron sulphide is first converted to sulphate and then this, through other stages, is converted into the hydrous sesquioxide (limonite), though the iron sometimes now occurs in the form of the anhydrous sesquioxide (hematite). This may have been derived from the limonite by dehydration, or, under certain conditions, may have been formed directly by the oxidation of iron pyrites. The oxidized copper-minerals in the upper part of the ore-deposit have been concentrated partly by segregation during alteration, and partly by the leaching of the associated materials. As a result of this, these minerals occur as seams, pockets, or irregular bodies, often a hundred feet or more in diameter, generally inclosed by, and often intimately associated with, the oxidized iron-materials which represent the gangue.

In the case of the Arizona deposits, alteration has progressed just far enough to increase greatly the value of the deposits without to any extent injuring it. Such products of alteration, however, are more or less soluble in surface-waters containing various organic and inorganic compounds, so that in a moist climate there is a constant tendency to leach them out and leave only the less soluble parts of the gangue. In Arizona, this stage has not yet progressed to a noticeable degree, and one reason for this may be the extreme dryness of the climate,

which affords opportunity for only comparatively slight percolation of surface-waters.

In the copper-deposits of Montana and the Appalachian region, however, a further stage of alteration is often observable. The copper-deposits of Butte City, Mont., are composed largely of chalcocite, with copper pyrites, bornite, enargite, iron pyrites, and other minerals, in a siliceous gangue. On the surface the copper in these deposits has been almost entirely oxidized and leached out, and the ore consists of a porous, rusty, siliceous mass, which was once mined for the small percentage of silver it contained. As depths were reached, the oxidized copper-minerals began to appear, and eventually the sulphides formed the mass of the veins. In this case, a further stage of alteration is seen than that in Arizona.

At Ducktown, in eastern Tennessee,[17] deposits of mixed iron and copper pyrites occur and have been altered in a somewhat similar manner on the surface. The copper-minerals have been leached out of the ferruginous gangue in the upper parts of the deposits, and for a depth of from 20 to 80 ft. or more, the deposits are composed simply of a porous mass of more or less hydrous sesquioxide of iron. Below this a part of the copper, which has been leached from above, has been carried down and deposited as a dark material, probably composed largely of oxides and sulphides of copper, and averaging sometimes from 20 to 25 per cent. or more in metallic copper. This material immediately overlies the unoxidized mixture of copper and iron pyrites, which averages only from 2 per cent. to 4 or 5 per cent. in copper. The commercial copper mined in this region came from the part of the deposit below the iron capping and above the unoxidized sulphides. When this was exhausted the mines had to be closed, for the unaltered sulphides were too poor to be utilized.

In Chile, Peru, and elsewhere in South America, changes in copper-deposits, somewhat similar to those described in the United States, frequently occur. In fact, the great reputation which Chile once had as a copper-producer was largely due to this surface-alteration, for the oxidized ore once supplied a rich

[17] J. D. Whitney, *The Metallic Wealth of the United States*, pp. 322 to 324.

and easily-treated source of copper; but when the mines reached the unoxidized sulphides, the ores became poor in copper and more difficult to treat, so that the copper industry of Chile began to decline. In that region, however, the oxidation has in some places extended down as far as 1,500 feet.

Alteration in Lead-Deposits.

In the case of lead-deposits, the mineral galena, which is the commonest ore, is frequently more or less altered on its surface-outcrops and converted to the sulphate (anglesite) and the carbonate (cerussite). The first product of oxidation is anglesite, but this is a soluble compound and readily unites with carbonic acid or soluble carbonates in surface-waters, forming the carbonate of lead, or cerussite. In rarer cases, other lead-minerals, like phosphates, may also be formed.

Alteration in Silver-Deposits.

Galena-deposits often contain silver, possibly sometimes in the same condition of sulphide as the galena, and this material is altered at the same time as the lead, with the formation of native silver, chloride of silver (cerargyrite), bromide of silver (bromyrite), iodide of silver (iodyrite), and various other minerals. The native silver is formed, probably, only after a preceding oxidation of the sulphide. Deposits carrying other unaltered silver-bearing minerals, such as the various silver sulphides, arsenides, antimonides, tellurides, etc., are, when exposed to surface-influences, affected in much the same way as the silver in argentiferous galena.

Alteration in Zinc-Deposits.

In the case of zinc, the most common ore is the sulphide known as blende. This mineral, like galena, is generally oxidized on the surface, and forms by other chemical changes the carbonate (smithsonite), the basic carbonate (hydrozincite), and the basic silicate (calamine), in a manner similar to that described in copper- and lead-ores.

In the cases of both lead and zinc, oxidized ores are very desirable for metallurgical purposes, and are much sought after. To be sure, the carbonates, sulphates, etc., of lead and zinc contain less of these metals than the pure sulphides, but

they occur in a more concentrated form than the sulphides, and, therefore, the ores containing them frequently carry as much or more of the metals than the ores containing the sulphides. Moreover, the oxidized ores are much more easy to treat and, therefore, have an additional value over the sulphide ores.

Alteration in Gold-Deposits.

In the case of gold-deposits, surface-alteration has a most marked effect, and probably in no class of deposits is the change of more geologic and economic importance. The typical unaltered condition of gold in nature is in association with iron pyrites in quartz, the gold being sometimes in such association with the pyrites that it cannot be separated by mechanical means, while in rarer cases it can be so separated. The effect of surface-oxidation on such a deposit, is first to convert the iron pyrites into a hydrated sesquioxide of iron, which permeates the white quartz, with which the pyrites is usually associated, and turns it into a rusty brown mass. The next stage is the gradual leaching-out of the hydrous sesquioxide by the action of surface-waters. The iron is, in this way, finally removed altogether, and the remaining product is a pure-white quartz, containing the gold which was originally in the iron pyrites, and which has remained stable during the oxidation and leaching of that mineral. Such quartz is usually porous and spongy, and is filled with cavities which represent the shapes of the original crystals of iron pyrites, and which, during an intermediate stage, have been partly filled with hydrous sesquioxide. This leaching, however, is rarely complete, and the quartz is usually stained brown on the surface.

In gold-deposits of this kind, other minerals, such as copper pyrites, galena, blende, etc., frequently occur, and when the deposit is affected by surface-influences, these minerals act in the manner already described under copper, lead, and zinc. It is not uncommon to see gold-bearing quartz stained green by oxidized copper-minerals, or black by manganese-minerals. Sometimes, especially in the Rocky Mountain region, gold occurs in the form of a telluride instead of in iron sulphide, and in such cases, the telluride is oxidized and the gold set free from its combined state. The gold, in being freed from pyrites

or other minerals, is not only concentrated by the removal of certain ingredients of the deposits, but it is brought into a condition in which it is much easier to treat than the unaltered part of the deposit, and, therefore, the upper parts of most gold-bearing veins are greatly enhanced in value. The ore from these parts is known as "free-milling" ore, because it can generally be ground and the gold extracted by direct amalgamation with mercury; while the ore in the unaltered parts of the deposit cannot usually be thus easily extracted, but must be smelted or treated by chlorination or some other more or less expensive process.

When such deposits as those described are eroded, the particles of gold separate from the quartz and are concentrated in the streams as placer-gold. These detrital deposits are the source of a large part of the gold of commerce, and, in fact, were once the source of most of it. Now, however, many of the richest placer-deposits known have been exhausted; and besides, the methods of treating the ores in the original deposits are better understood, so that the latter are supplying yearly a larger and larger percentage of the gold-production of the world. Hence, it will be seen that, in gold-deposits, surface-alteration not only plays an important part in freeing the gold from the iron pyrites, but also in forming placer-deposits. Detrital deposits similar to gold-placers and carrying various other materials are not at all uncommon, as in the cases of the platinum group of metals, cassiterite, diamonds and many other gems, chromite and magnetite sands, and, in fact, even with some of the more common ores, as with the iron-conglomerate at Iron Mountain, Mo.

Alteration in Tin-Deposits.

In tin-deposits, the typical mode of occurrence of the metal is in veins, dikes, or country-rocks, in the form of the oxide known as cassiterite. Cassiterite is not easily affected chemically by surface-influences, so that it is not much changed by superficial alteration, but, for this very reason, its concentration is most markedly affected by surface-alteration, for in the erosion of tin-bearing deposits the masses of cassiterite are broken up and carried off mechanically by surface-waters, to be deposited somewhere else in the form of gravel-beds, instead of

being dissolved and possibly disseminated. In this transition, the fragments of cassiterite are largely separated from the accompanying materials by reason of their greater specific gravity, and hence, gravel-deposits rich in cassiterite frequently occur. These represent the stream-tin of the miner, and have been formed in much the same manner as have the placer gold-deposits. Some chemical action, however, has gone on in the tin-ore itself, but this seems to have been simply a process of solution and redeposition, as is seen in the pseudomorphs of cassiterite after other minerals and in the impregnations of animal remains in Cornwall, such as antlers, with oxide of tin.[18]

Alteration in Antimony-Deposits.

In many antimony-deposits, alteration similar to that described in some of the deposits already mentioned frequently occurs. The metal occurs most commonly as the sulphide known as stibnite. By alteration, however, this passes into the oxides valentinite, senarmontite, cervantite, stibiconite, etc., or into the combined sulphide and oxide known as kermesite. Valentinite and senarmontite have the same chemical composition but differ in their crystalline forms. Native antimony sometimes occurs, and this also, by alteration, gives rise to the oxides.

Alteration in Bismuth-Deposits.

The allied metal bismuth occurs most commonly as native bismuth, though the sulphide (bismuthinite), the selenide (guanajuatite), the telluride (tetradymite), etc., also occur. Native bismuth, by alteration, forms the carbonate (bismutite) and probably also the oxide (bismite) and the silicate (eulytite).

Alteration in Mercury-Deposits.

In the case of mercury the metal commonly occurs as the sulphide (cinnabar), though other mercury-minerals also occur. By the alteration of cinnabar and some of the other mercury-minerals, metallic mercury is set free and occurs as globules or filling cavities in the ore.

[18] J. H. Collins, *Mineralogical Magazine*, vol. iv., p. 115 (1882).

Alteration in Molybdenum-Deposits.

Another case of surface-alteration in metalliferous deposits is that seen in molybdenite. This mineral is the sulphide of the metal molybdenum, and often occurs in quartz or calcite veins in the crystalline rocks of parts of Canada, and in many ore-deposits of the Rocky mountains and elsewhere. By surface-oxidation, molybdenite passes into a brilliant yellow oxide of molybdenum, commonly known as molybdite or molybdic ocher, which, in the Canadian region, occurs as a powdery coating on the cleavage-planes of the molybdenite.

Alteration in Other Deposits.

Superficial alteration like that already described in various deposits occurs also in many others not yet mentioned, as in aluminum-, nickel-, cobalt-, chromium-, tungsten-, and many rarer deposits, but the changes already described show the general features of the subject. It may be said, however, that one of the important ores of aluminum, known as bauxite, is probably derived from the alteration of feldspar under certain conditions; and its source, therefore, is not altogether unlike that of the hydrous sesquioxide of iron derived from the alteration of certain silicates. The conditions during formation, however, were probably quite different.

IV. The Formation of Haloid Compounds in Ore-Deposits in Arid Regions.

The formation of chlorides and other haloid compounds has already been mentioned as one of the phenomena of superficial alteration in ore-deposits. As soluble chlorides and sometimes other haloid compounds are common in surface-waters, chlorides and the allied compounds are not at all uncommon as alteration-products, especially in such cases as that of silver, where the chloride, bromide, and iodide are insoluble compounds, and are not leached out. For this reason, chloride ores of silver are found to a greater or less extent in almost all silver-districts in America, Europe, and elsewhere, but the occurrence of such compounds in very large quantities in certain parts of North and South America deserves special explanation.

Over a large part of the arid region of the West, lying be-

tween the Rocky mountains and the Sierra Nevada, ores containing chloride of silver (cerargyrite) are abundant, and sometimes the bromides and iodides also occur; in fact, parts of this region are characterized by chloride ores. They are especially well developed in parts of New Mexico, Arizona, Utah, Nevada and other States and Territories, and it seems probable that their abundance can be traced to the effect of the peculiar climatic conditions which have prevailed in that region in late geologic times. Most of this arid country was once covered with numerous bodies of water, some of them of great size. In late geologic times, however, these began to dry up, until their waters no longer rose high enough to have outlets, and then, as a natural result, they became highly impregnated with salt and other saline matter. Finally, they became desiccated, leaving deposits of various earthy and saline materials in their old basins, and among the most common of these was common salt. It seems probable that the abundance of chloride ores is due to the action of this salt on the pre-existing ore-deposits of the region, in the basins of the lakes, and that the smaller quantities of bromides and iodides were formed by a similar action of the soluble bromides and iodides in association with the salt. Such ores, in some of the mines that have gone to sufficient depths, have passed into various other silver-compounds, such as the sulphide (argentite), argentiferous galena, etc., which represent the original condition of the ores. This transition proves the chlorides and other haloid compounds to be of only superficial extent.

This transition to haloid compounds is not confined to silver-ores, for the basic chloride of copper (atacamite) occurs at Jerome, in Arizona, and both chlorides and bromides of copper occur in the Bloody Tanks district west of Globe, in Arizona, though here, as elsewhere in Arizona, the other copper-minerals already mentioned, such as carbonates, sulphides, etc., form the bulk of the copper-deposits.

In parts of Mexico, Chile, and Peru, where saline materials have collected in a manner somewhat similar to that in the arid regions of the United States, the chloride of silver is one of the important ores mined, and it sometimes occurs intimately mixed with chloride of sodium, or common salt, forming the mineral huantajayite, or the lechedor of the miners. The

bromides of silver are also abundant in Chile, and, in fact, at the mines of Chañarcillo, a common ore is the double chloride and bromide known as embolite. Again, the atacamite, or basic chloride of copper, from the Desert of Atacama is well known.

It seems probable that this transformation of the silver- and copper-minerals did not necessarily occur exclusively while the deposits were covered by saline lakes, but may have occurred even more actively afterwards, when the surface-waters were highly impregnated with chlorides from the residue left by the lakes, and when oxidation in the ore-deposits was much more active than when they were covered by water. This seems all the more likely when we consider that the original silver- and copper-minerals probably had to be oxidized before they were converted to chlorides, etc. Of course the oxidation may have partly occurred before, or during, the existence of the lakes, but in many cases it probably also occurred after they were desiccated.[19]

V. Summary.

It will be seen from the above discussion that:

(1) After the deposition of ore-deposits and their subsequent exposure to surface-influences, such as air, water and the materials contained in it, changes of temperature, etc., chemical and physical alterations occur which cause a total change in the mineralogical condition, and generally in the economic value, of the ore-deposit.

(2) The process of this alteration is primarily one of oxidation and generally of hydration, and both of these actions may go on alone, but generally both have their effect on the same material. The other materials in solution in surface-waters also react on the substances in the ore-deposit, either before or after the oxidation of the latter, though generally after at least partial oxidation, and form various compounds different from those originally in the deposit. The difference, however, with few exceptions, is not in the metal or other base which forms the important feature of the deposit, but in the acidic portion

[19] Chlorides of other materials than silver and copper may also have been formed by a similar process, but the solubility of many metallic chlorides would prevent their being accumulated in any but very dry regions.

or material representing this portion of the mineral. Thus, sulphide of copper may be altered to carbonate of copper, but the base remains the same. The action of surface-influences is in rare cases one of reduction, which, however, often follows a previous oxidation. The process of alteration also frequently causes a leaching of certain ingredients of the ore-deposit, either with or without previous oxidation, as in the removal of iron pyrites, calcite, etc. It also sometimes renders a hitherto-worthless material valuable by the introduction of a valuable constituent, as in the replacement of carbonate of lime by phosphate of lime. It also causes the concentration, by capillary action in soils, of certain deposits like niter, etc. The compounds formed with different ore-deposits vary with the ores affected and the stability of the compounds formed by the action of the materials in the surface-waters on the constituents of the ores.

(3) The physical effect of superficial alteration is generally to make the deposit more open and porous, to cause it to shrink, and, in some cases, to convert it into a loose material of the consistency of sand and clay. In some cases, however, especially where hydration is active, expansion may be caused.

(4) Superficial alteration extends downward as far as surface-influences are able to act, though generally alteration is not complete down to the possible limit. The depth of alteration depends on the topography of the region, the nature of the rocks, and on the climate. In glaciated regions, the glacial action has swept away the products of alteration, and sufficient time has not elapsed since then for alteration to have gone on to any great extent, but in many other regions the products of alteration have accumulated to considerable depths. The depth of alteration, under different conditions, varies from a fraction of a foot to 1,500 ft. or possibly more.

(5) Superficial alteration is well illustrated in iron-, manganese-, copper-, lead-, zinc-, silver-, gold-, tin-, and many other deposits. For special descriptions see text.

(6) The accumulation of soluble saline materials, like salt, on the surface has a very important effect in converting certain materials in underlying ore-deposits to chlorides, etc.

No. 7.

Some Mines of Rosita and Silver Cliff, Colorado.

BY S. F. EMMONS, WASHINGTON, D. C.

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Mines in Rhyolite near Silver Cliff.

Geological Sketch.—The rhyolite area near Silver Cliff includes what may be called the Silver Cliff plateau, with Round mountain and the intervening valley. The plateau is about 2 miles long and 1 mile wide. From its northern part rise the White hills, which have no special topographic importance, as their highest point is only 400 ft. above the northern edge of the rhyolite mass. Round mountain, on the other hand, is a quite sharply pointed conical hill, so steep-sided as to constitute an important topographic feature, although its elevation above the plains around it is barely 700 ft. The summit of Round mountain is dense banded rhyolite, with steep, irregular dip; the southern end is breccia containing fragments of the banded rock. There are slight exposures of glassy forms of rhyolite on the lower slopes. On the east, the Archæan rocks extend half-way up the side of the mountain, and the contact between them and the rhyolite is vertical, or dips steeply to the west. This mountain is supposed to be at the vent from which the rhyolite of the plateau was poured out.

The Silver Cliff plateau occupies the site of a former basin, in which at one time there was probably a lake. At the time of the rhyolitic outburst of the Rosita hills there was a local eruption of the same character in this region, commencing with showers of volcanic ash and of rock-fragments, which filled the lake and built up about it hills which have since been removed in great measure by erosion. At present the southern half of the plateau is capped by solid lava to a depth in places of 150 ft. The cliff of blackened rhyolite on the southern edge, where the main discovery of ore was made, is from 30 to 50 ft.

high. In many places, as in the Vanderbilt mine, the rock is plainly fragmental and stratified, and has a well-defined dip. The contact of Archæan and rhyolite along the western border is a gently-undulating surface, and in most of the prospect-holes the Archæan is much broken and resembles a breccia. The northern half of the area is breccia and tuff, except a few dikes of massive rock. At the Songbird and Mountain View mines, and along the western border generally, the gneiss under the rhyolite has been much altered and is locally ore-bearing, carrying magnetite, pyrite, and some galena, as in the Immortal and Keystone mines. Near the Sunrise, and along the eastern border as far south as the Vanderbilt, the rock is a finely-bedded tuff, dipping south and west. The thickness of fragmental material below the highest point of the hills is more than 550 ft. These beds terminate abruptly to the south along an east-and-west line running near the Vanderbilt, which Mr. Cross thinks may be a fault-line.

The massive rock is everywhere characterized by a banded or fluidal structure, and in it topaz and garnet have been found. Under the massive lava on the southern portion of the plateau is pitchstone or glassy rhyolite, about 50 ft. thick, with about as much more below, containing spherulites, which, when decomposed, form a boulder-zone. These glassy rocks outcrop around the cliff to the south and east, and are found in cellars in the town of Silver Cliff.

Surface-Deposits.—The original outcrop of the ore-bearing rhyolite on the Silver Cliff and Racine Boy claims was apparently nothing more than the ordinary banded rhyolite, stained and blackened by oxides of manganese, extensively cracked and fissured, and carrying little flakes of chloride of silver in the cracks. As far as known, no other metallic minerals were detected, nor was there any definite boundary or regularity of form to the part that constituted the ore. An area several hundred feet in diameter and from 30 to 50 ft. thick was thus found to be ore-bearing. When examined by us in the quarry, the principal set of joints or rock-fractures were observed to run nearly northwest and southeast, and it was on these that the most silver was found. On some of these cracks was a considerable coating of clear black manganese oxide; in others, where there was more iron oxide, the coating had a metallic

luster; and it was on the latter, according to the observations of the miners who were sorting the ore, that the principal values were found. A set of secondary joints or fractures, crossing the main joints nearly at right angles and reaching to the surface, could be observed along the benches of the quarry. These also were heavily coated with manganese oxide, and carried ore. It was but rarely, at that time, that the flakes of horn-silver could be detected by the naked eye. Our observations indicated that the horn-silver was more frequently deposited on small cracks, adjoining those filled by iron and manganese oxides, and apparently of later formation. The light-colored mass of the rock had a faint pink tinge, and a specimen analyzed contained 0.06 per cent. of manganese oxide. It was the experience of the miners that the silver-values did not occur outside of the stained zone.

When the ore-body was first worked, it is said to have contained from 35 to 50 oz. of silver per ton, but it gradually decreased in value as it was taken at a greater distance from the surface. It is said that, while the mills were running, the rock was not sorted, but sent in bulk to the crusher. The last mill-runs are said to have assayed only about 7 oz. to the ton, and the greater part of this went off in the tailings.

The ore taken from the quarry was sorted, so as to average from 50 to 60 oz. per ton, at one time; but this fell off later, and it was apparently so low finally as not to pay for working.

It has been a cause of much fruitless speculation that the amalgamating-mills were so unsuccessful in treating this ore. It is generally conceded that much the larger portion of the silver was carried away in the tailings, which were afterwards profitably concentrated by hand-jigs. A sample of these tailings, carefully quartered down, yielded in the laboratory of the Survey 0.13 per cent. of sulphur, which is sufficient to combine with the silver contained and form sulphides. It is also said that a small amount of antimony has been found in the ore by those who smelted it.

If the silver is generally in the form of sulphide, it would naturally be difficult of amalgamation, and the presence of antimony would heighten that difficulty.

Small amounts of ore were also found near the surface at many other points on the plateau, which, though not compara-

ble in amount to the Silver Cliff body, were sufficient to encourage prospecting to such an extent that over 400 prospect-holes were counted there at the time of our examination. For the most part they had been already abandoned, and there was nothing to show how the ore, if any there was, occurred. Among the more prominent ones, which actually produced considerable values, may be named the Boulder, Vanderbilt, King of the Valley and Silver Bar (formerly the Kate).

Deep Deposits of the Geyser Mine.

The only mine-workings that have extended to any considerable depth on the plateau, say over 100 ft., are those of the Security-Geyser mine. As far as is known, the ore of all the plateau-deposits had given out, really or apparently, within considerably less than 100 ft. of the surface. The ore was always chloride of silver where its character could be distinguished. That from the Kate (Silver Bar) claim, worked in early days, is said to have contained some gold also; but this is the only case reported and the statement has not been verified. It does not seem likely that silver would be accompanied by gold in one place and free from it in all the others. As will be seen later, of the two shipments to smelters of ore from the bottom of the Geyser shaft, one contained only 0.1 oz. of gold per ton, the other but a trace.

It is only through the underground workings of the Geyser shaft, therefore, that it has been possible to obtain any information with regard to the conditions of ore-deposition in depth. The data which it has been possible to obtain with regard to them in occasional visits during past years will therefore be given in considerable detail.

The Geyser shaft, as it is now called, is located 350 ft. north, a little west, of the mouth of the adit leading from the floor of the Silver Cliff quarry, and its collar is 104 ft. above that level. It was originally intended to sink the shaft only 500 ft., it being supposed, from the position of the various observable contacts of the rhyolite with the underlying Archæan, that the former was a rather shallow body, and that the underlying granite and gneiss would be reached within the depth named. It was, later, decided to prepare for greater depths, and the hoisting-machinery was given greater capacity. The limit of this ca-

pacity was reached in the summer of 1894, when a depth of 2,100 ft. was attained. Entirely new and heavier machinery, with a capacity of 4,500 ft., was then ordered, which is now (May, 1896) in working-order, and sinking has been resumed.

Mine-Levels.—The first exploring-levels or drifts were started at a depth of 500 ft. These were run 500 ft. west and 700 ft. east; likewise some distance in a southerly direction. At 750 ft., levels were run to the east and south, and one branch passed directly under the quarry. Below this, levels were run at 1,450, 1,850, 2,000, and 2,100 ft. from the surface, respectively. The general direction of exploration in these levels appears to have been to the west and northwest, but the 1,450-ft. level had a drift running southward. Accurate maps of the respective levels could not be obtained, but, in a general way, it is estimated that the main exploring-drifts have a linear extent of about 1.5 miles at the different levels, and that about 600,000 sq. ft. of area was more or less thoroughly explored. Fig. 1 (Fig. 7 of original paper) gives a somewhat diagrammatic representation of the ground explored.

Country-Rocks.—For the first 150 ft. the shaft passed through banded rhyolite. In the tunnel leading to the shaft, a narrow zone or band of this rock was found to be changed into a plastic white clay, which was almost pure kaolin.

Below the solid rhyolite was about 50 ft. of pitchstone, then about the same thickness of the boulder or spherulitic zone. Veins and crystals of calcite were found in the rhyolite under the pitchstone. From 250 ft. down to about 1,900 ft. the shaft passed through white rhyolitic tuff and breccia, the former often distinctly stratified and generally looking like white sandstone, much kaolinized. The breccia varies from fine to coarse, and contains fragments of all the varieties of Archæan rocks found in the region; but no eruptive, other than rhyolite, was observed among the fragments. Some of the Archæan fragments are kaolinized and disintegrated; others are quite fresh. The green decomposition-product of hornblende and mica was in one place thought to be a copper-stain.

Here and there through the tuff, as far as the 2,000-ft. level, fragments of charcoal or carbonized wood were observed (the special localities are marked by a cross on the section in Fig. 1). At 335 ft., pieces 2 ft. long are said to have been found in the shaft.

The bedding of the tuff was found to be, for the most part, nearly horizontal. In the shaft a slight dip to the west was noted at times for considerable vertical distances. In the drifts,

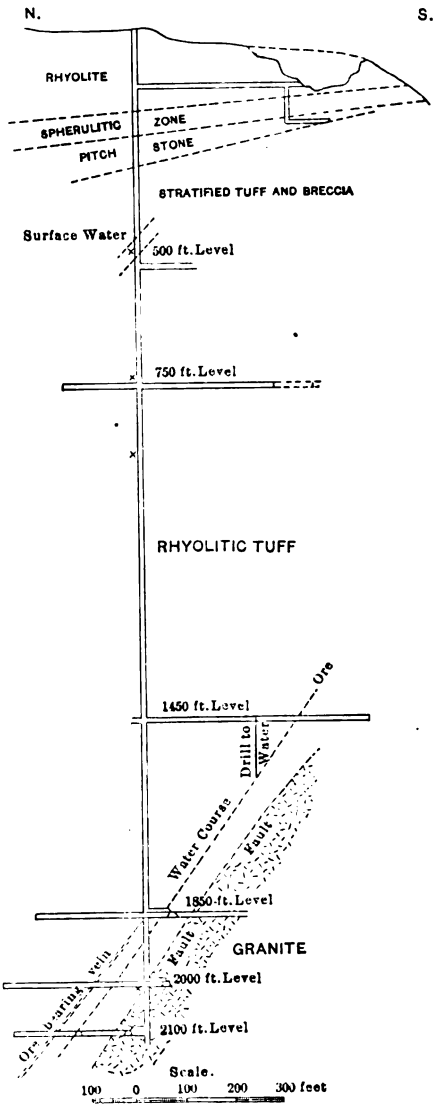

FIG. 1.—SECTION THROUGH GEYSER SHAFT.

the dip to the west or northwest is more marked, in a general way, to the southeast of the shaft, and in one place, for a short distance, this dip was 75°. In the shaft there appears to have

been a somewhat irregular alternation of white tuff and breccia. For instance, the former was found continuously from 775 to 905 ft., and from there to 1,000 ft. the rock was mostly breccia, at times with so many large fragments of Archæan, up to 2.5 ft. in diameter, that it was thought the solid formation would soon be reached.

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In the 2,100-ft. level, drifts run only north and west, and the contact, as contrasted with that in the level above, has an inclination to the northeast. The contact on this level is not sharp and well defined, but rather a broken zone, first of very coarse fragments of granite and gneiss, then of normal rhyolitic breccia with small fragments of granite and gneiss. The three lower levels have been run from 300 to 500 ft. north and west in this material, which is sometimes hard and jaspery and of dark-red color, but bleaches on exposure to the air. It is traversed by planes of movement, sometimes irregular and curving, but all having a general northwest strike. Beyond one of these planes is a dark bluish rock, supposed by the miners to be limestone because it effervesces freely with acid, but, on microscopic examination, found to be a decomposed basic eruptive, containing considerable calcite.

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Gold	Trace.	*a*
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Copper (wet assay)	1.50	2.30
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Manganese	1.20	0.80
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Of earthy minerals, the most common are barite, calcite, and quartz, the latter generally in the chalcedonic form. Fragments of country-rock are found in the vein, more or less rounded, and changed on the outer part into hornstone-like material, which, in turn, is coated with galena, barite, etc. Rounded cavities in the vein-material are often filled with a white powder, apparently an infiltrated decomposition-product of the rhyolitic tuff.

Water-Courses.—This mine has proved unusually dry for the region. In the upper part of the shaft the first considerable flows of water came in at 340, 390, and especially at 420 ft. This water, collected at the 500-ft. level, amounted to 250 gal. per minute, and was undoubtedly vadose or surface-water, and probably seeped in from the surrounding country. At 945 ft.

it had decreased to 65 gal. per minute, and below 1,000 ft. had practically ceased, the little water that was found being probably due to leakage along the shaft.

In the 1,450-ft. level what may be considered subterranean or deep waters were first struck. They were not very abundant, and were only slightly charged with gas. At one point on the south drift there was a slight deposit of tufa. A considerable flow was obtained from a vertical drill-hole sunk 300 ft. downward from this level.

In the 1,850-, 2,000-, and 2,100-ft. levels there are many small water-courses, from which proceeds a constant flow of water, not very great in aggregate amount, but highly charged with carbonic acid gas, so that there is a constant hissing, sputtering, and rumbling, and the water is ejected with such force as to go entirely across the drift at some points. These waters apparently ascend along fissures having a general parallelism with the ore-bearing fissure; but no water proceeds from the vein itself. They often come into the drifts through small cracks or cross-fissures at an angle with the direction of the main system. As they emerge into the air of the drift they deposit freely a calcareous tufa or sinter on the wall around the crack or orifice out of which they flow. This sinter is sometimes white, sometimes highly iron-stained; it has the texture and the peculiar wavy or ripple-marked surface characteristic of the sinters of the Yellowstone Park. In some places it takes a pisolitic form. Again its surface has a shiny glaze. It deposits very rapidly in some places. At one point on the 2,000-ft. level, which had been opened only four months, the water issuing from a minute vertical crack on the side of the drift had built out a little ridge of sinter over the crack, 1.5 in. from its base and less than 0.5 in. thick.

The water-courses are most active and abundant near the vein or on the line of its extension. On the 2,000-ft. level, where the vein splits to the northwest, the water comes in on all sides; and when the shaft was first opened, the escape of carbonic acid gas was so abundant at this point that it filled the lower 5 ft. of all the drifts on this level and the shaft below the level so that no light would burn, and the miners were obliged to abandon work until a blower could be put in operation to drive the gas out. Even now, a light is soon extinguished

if put at the bottom of the drift. The water-bearing fissures are mostly in the rhyolitic tuff, but a few are found in the Archæan, which shows evidence of faulting within itself, in slickensided clay seams and zones of brecciation. The water-bearing fissures decrease in number and in strength of flow as the distance from the line of the ore-bearing fissure increases. The abundant escape of gas is the most striking feature of these water-courses. Even where no water comes into the drift, one can often hear the bubbling and sputtering of the escaping gas in an adjoining fissure.

The temperature could not be accurately determined, but is about the same as that of the air in the drift at the 2,000-ft. level, viz., 80° F.

Analyses of Sinters.—Three typical specimens of sinter from the 2,000-ft. level were selected for analysis: one of the perfectly white, with very slight iron-stain; one white and brown (both showing the ripple-marked structure well); a third of the pisolitic sinter, strongly iron-stained. They were analyzed by W. F. Hillebrand, with the following results:

Analyses of Sinters from the 2,000-Ft. Level, Geyser Mine.

	White.	White and Brown.	Pisolitic Brown.
	Per Cent.	Per Cent.	Per Cent.
Silica and insoluble	0.08	0.10	0.17
CaO	53.11	52.60	52.59
CO_2	42.98	42 57	42.03
Fe_2O_3	0.20	1.08	1.82
Mn_2O_3 (Mn_3O_4?)	*a* 0.026	*a* 0.03	Undet.
SrO	0.17	0.26	0.22
MgO	1.50	1.39	1.01
K_2O	0.03	0.03	0.04
Na_2O	0.17	0.16	0.09
Li_2O	Trace.	Trace.	Trace.
H_2O below 110° C.	0.33	0.51	0.53
H_2O above 110° C.	0.88	0.72	0.87
SO_3	0.29	0.50	0.58
P_2O_5	Trace.	Trace.	Trace.
Cl	Faint trace.	Faint trace.	Faint trace.
Total	99.766	99.95	99.95

a Manganese was estimated on 34 g. The same samples showed also minute traces of lead, copper, nickel, cobalt, zinc, alumina, and a double trace of antimony.

On comparing these analyses with those of the waters which follow, it appears that, under the influence of free access of air,

or material representing this portion of the mineral. Thus, sulphide of copper may be altered to carbonate of copper, but the base remains the same. The action of surface-influences is in rare cases one of reduction, which, however, often follows a previous oxidation. The process of alteration also frequently causes a leaching of certain ingredients of the ore-deposit, either with or without previous oxidation, as in the removal of iron pyrites, calcite, etc. It also sometimes renders a hitherto-worthless material valuable by the introduction of a valuable constituent, as in the replacement of carbonate of lime by phosphate of lime. It also causes the concentration, by capillary action in soils, of certain deposits like niter, etc. The compounds formed with different ore-deposits vary with the ores affected and the stability of the compounds formed by the action of the materials in the surface-waters on the constituents of the ores.

(3) The physical effect of superficial alteration is generally to make the deposit more open and porous, to cause it to shrink, and, in some cases, to convert it into a loose material of the consistency of sand and clay. In some cases, however, especially where hydration is active, expansion may be caused.

(4) Superficial alteration extends downward as far as surface-influences are able to act, though generally alteration is not complete down to the possible limit. The depth of alteration depends on the topography of the region, the nature of the rocks, and on the climate. In glaciated regions, the glacial action has swept away the products of alteration, and sufficient time has not elapsed since then for alteration to have gone on to any great extent, but in many other regions the products of alteration have accumulated to considerable depths. The depth of alteration, under different conditions, varies from a fraction of a foot to 1,500 ft. or possibly more.

(5) Superficial alteration is well illustrated in iron-, manganese-, copper-, lead-, zinc-, silver-, gold-, tin-, and many other deposits. For special descriptions see text.

(6) The accumulation of soluble saline materials, like salt, on the surface has a very important effect in converting certain materials in underlying ore-deposits to chlorides, etc.

No. 7.

Some Mines of Rosita and Silver Cliff, Colorado.

BY S. F. EMMONS, WASHINGTON, D. C.

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Mines in Rhyolite near Silver Cliff.

Geological Sketch.—The rhyolite area near Silver Cliff includes what may be called the Silver Cliff plateau, with Round mountain and the intervening valley. The plateau is about 2 miles long and 1 mile wide. From its northern part rise the White hills, which have no special topographic importance, as their highest point is only 400 ft. above the northern edge of the rhyolite mass. Round mountain, on the other hand, is a quite sharply pointed conical hill, so steep-sided as to constitute an important topographic feature, although its elevation above the plains around it is barely 700 ft. The summit of Round mountain is dense banded rhyolite, with steep, irregular dip; the southern end is breccia containing fragments of the banded rock. There are slight exposures of glassy forms of rhyolite on the lower slopes. On the east, the Archæan rocks extend half-way up the side of the mountain, and the contact between them and the rhyolite is vertical, or dips steeply to the west. This mountain is supposed to be at the vent from which the rhyolite of the plateau was poured out.

The Silver Cliff plateau occupies the site of a former basin, in which at one time there was probably a lake. At the time of the rhyolitic outburst of the Rosita hills there was a local eruption of the same character in this region, commencing with showers of volcanic ash and of rock-fragments, which filled the lake and built up about it hills which have since been removed in great measure by erosion. At present the southern half of the plateau is capped by solid lava to a depth in places of 150 ft. The cliff of blackened rhyolite on the southern edge, where the main discovery of ore was made, is from 30 to 50 ft.

high. In many places, as in the Vanderbilt mine, the rock is plainly fragmental and stratified, and has a well-defined dip. The contact of Archæan and rhyolite along the western border is a gently-undulating surface, and in most of the prospect-holes the Archæan is much broken and resembles a breccia. The northern half of the area is breccia and tuff, except a few dikes of massive rock. At the Songbird and Mountain View mines, and along the western border generally, the gneiss under the rhyolite has been much altered and is locally ore-bearing, carrying magnetite, pyrite, and some galena, as in the Immortal and Keystone mines. Near the Sunrise, and along the eastern border as far south as the Vanderbilt, the rock is a finely-bedded tuff, dipping south and west. The thickness of fragmental material below the highest point of the hills is more than 550 ft. These beds terminate abruptly to the south along an east-and-west line running near the Vanderbilt, which Mr. Cross thinks may be a fault-line.

The massive rock is everywhere characterized by a banded or fluidal structure, and in it topaz and garnet have been found. Under the massive lava on the southern portion of the plateau is pitchstone or glassy rhyolite, about 50 ft. thick, with about as much more below, containing spherulites, which, when decomposed, form a boulder-zone. These glassy rocks outcrop around the cliff to the south and east, and are found in cellars in the town of Silver Cliff.

Surface-Deposits.—The original outcrop of the ore-bearing rhyolite on the Silver Cliff and Racine Boy claims was apparently nothing more than the ordinary banded rhyolite, stained and blackened by oxides of manganese, extensively cracked and fissured, and carrying little flakes of chloride of silver in the cracks. As far as known, no other metallic minerals were detected, nor was there any definite boundary or regularity of form to the part that constituted the ore. An area several hundred feet in diameter and from 30 to 50 ft. thick was thus found to be ore-bearing. When examined by us in the quarry, the principal set of joints or rock-fractures were observed to run nearly northwest and southeast, and it was on these that the most silver was found. On some of these cracks was a considerable coating of clear black manganese oxide; in others, where there was more iron oxide, the coating had a metallic

luster; and it was on the latter, according to the observations of the miners who were sorting the ore, that the principal values were found. A set of secondary joints or fractures, crossing the main joints nearly at right angles and reaching to the surface, could be observed along the benches of the quarry. These also were heavily coated with manganese oxide, and carried ore. It was but rarely, at that time, that the flakes of horn-silver could be detected by the naked eye. Our observations indicated that the horn-silver was more frequently deposited on small cracks, adjoining those filled by iron and manganese oxides, and apparently of later formation. The light-colored mass of the rock had a faint pink tinge, and a specimen analyzed contained 0.06 per cent. of manganese oxide. It was the experience of the miners that the silver-values did not occur outside of the stained zone.

When the ore-body was first worked, it is said to have contained from 35 to 50 oz. of silver per ton, but it gradually decreased in value as it was taken at a greater distance from the surface. It is said that, while the mills were running, the rock was not sorted, but sent in bulk to the crusher. The last mill-runs are said to have assayed only about 7 oz. to the ton, and the greater part of this went off in the tailings.

The ore taken from the quarry was sorted, so as to average from 50 to 60 oz. per ton, at one time; but this fell off later, and it was apparently so low finally as not to pay for working.

It has been a cause of much fruitless speculation that the amalgamating-mills were so unsuccessful in treating this ore. It is generally conceded that much the larger portion of the silver was carried away in the tailings, which were afterwards profitably concentrated by hand-jigs. A sample of these tailings, carefully quartered down, yielded in the laboratory of the Survey 0.13 per cent. of sulphur, which is sufficient to combine with the silver contained and form sulphides. It is also said that a small amount of antimony has been found in the ore by those who smelted it.

If the silver is generally in the form of sulphide, it would naturally be difficult of amalgamation, and the presence of antimony would heighten that difficulty.

Small amounts of ore were also found near the surface at many other points on the plateau, which, though not compara-

ble in amount to the Silver Cliff body, were sufficient to encourage prospecting to such an extent that over 400 prospect-holes were counted there at the time of our examination. For the most part they had been already abandoned, and there was nothing to show how the ore, if any there was, occurred. Among the more prominent ones, which actually produced considerable values, may be named the Boulder, Vanderbilt, King of the Valley and Silver Bar (formerly the Kate).

Deep Deposits of the Geyser Mine.

The only mine-workings that have extended to any considerable depth on the plateau, say over 100 ft., are those of the Security-Geyser mine. As far as is known, the ore of all the plateau-deposits had given out, really or apparently, within considerably less than 100 ft. of the surface. The ore was always chloride of silver where its character could be distinguished. That from the Kate (Silver Bar) claim, worked in early days, is said to have contained some gold also; but this is the only case reported and the statement has not been verified. It does not seem likely that silver would be accompanied by gold in one place and free from it in all the others. As will be seen later, of the two shipments to smelters of ore from the bottom of the Geyser shaft, one contained only 0.1 oz. of gold per ton, the other but a trace.

It is only through the underground workings of the Geyser shaft, therefore, that it has been possible to obtain any information with regard to the conditions of ore-deposition in depth. The data which it has been possible to obtain with regard to them in occasional visits during past years will therefore be given in considerable detail.

The Geyser shaft, as it is now called, is located 350 ft. north, a little west, of the mouth of the adit leading from the floor of the Silver Cliff quarry, and its collar is 104 ft. above that level. It was originally intended to sink the shaft only 500 ft., it being supposed, from the position of the various observable contacts of the rhyolite with the underlying Archæan, that the former was a rather shallow body, and that the underlying granite and gneiss would be reached within the depth named. It was, later, decided to prepare for greater depths, and the hoisting-machinery was given greater capacity. The limit of this ca-

pacity was reached in the summer of 1894, when a depth of 2,100 ft. was attained. Entirely new and heavier machinery, with a capacity of 4,500 ft., was then ordered, which is now (May, 1896) in working-order, and sinking has been resumed.

Mine-Levels.—The first exploring-levels or drifts were started at a depth of 500 ft. These were run 500 ft. west and 700 ft. east; likewise some distance in a southerly direction. At 750 ft., levels were run to the east and south, and one branch passed directly under the quarry. Below this, levels were run at 1,450, 1,850, 2,000, and 2,100 ft. from the surface, respectively. The general direction of exploration in these levels appears to have been to the west and northwest, but the 1,450-ft. level had a drift running southward. Accurate maps of the respective levels could not be obtained, but, in a general way, it is estimated that the main exploring-drifts have a linear extent of about 1.5 miles at the different levels, and that about 600,000 sq. ft. of area was more or less thoroughly explored. Fig. 1 (Fig. 7 of original paper) gives a somewhat diagrammatic representation of the ground explored.

Country-Rocks.—For the first 150 ft. the shaft passed through banded rhyolite. In the tunnel leading to the shaft, a narrow zone or band of this rock was found to be changed into a plastic white clay, which was almost pure kaolin.

Below the solid rhyolite was about 50 ft. of pitchstone, then about the same thickness of the boulder or spherulitic zone. Veins and crystals of calcite were found in the rhyolite under the pitchstone. From 250 ft. down to about 1,900 ft. the shaft passed through white rhyolitic tuff and breccia, the former often distinctly stratified and generally looking like white sandstone, much kaolinized. The breccia varies from fine to coarse, and contains fragments of all the varieties of Archæan rocks found in the region; but no eruptive, other than rhyolite, was observed among the fragments. Some of the Archæan fragments are kaolinized and disintegrated; others are quite fresh. The green decomposition-product of hornblende and mica was in one place thought to be a copper-stain.

Here and there through the tuff, as far as the 2,000-ft. level, fragments of charcoal or carbonized wood were observed (the special localities are marked by a cross on the section in Fig. 1). At 335 ft., pieces 2 ft. long are said to have been found in the shaft.

The bedding of the tuff was found to be, for the most part, nearly horizontal. In the shaft a slight dip to the west was noted at times for considerable vertical distances. In the drifts,

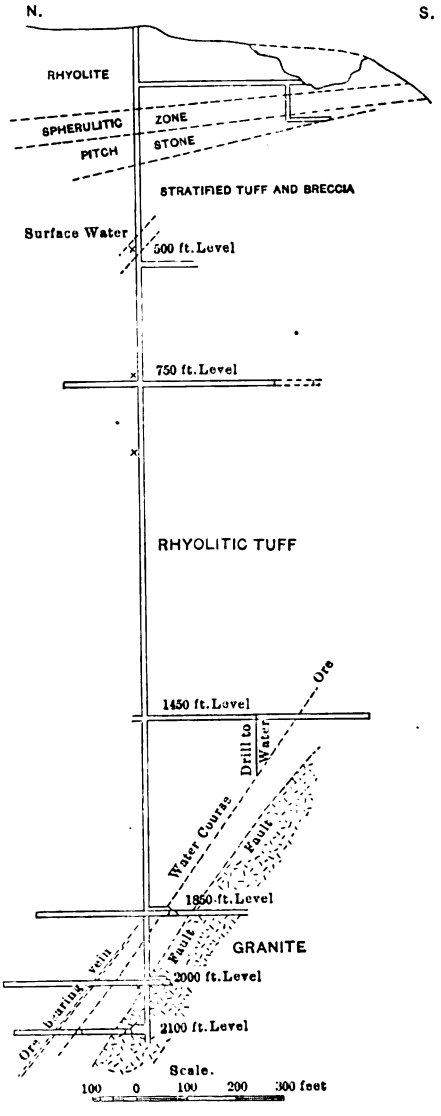

FIG. 1.—SECTION THROUGH GEYSER SHAFT.

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been a somewhat irregular alternation of white tuff and breccia. For instance, the former was found continuously from 775 to 905 ft., and from there to 1,000 ft. the rock was mostly breccia, at times with so many large fragments of Archæan, up to 2.5 ft. in diameter, that it was thought the solid formation would soon be reached.

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In the 2,100-ft. level, drifts run only north and west, and the contact, as contrasted with that in the level above, has an inclination to the northeast. The contact on this level is not sharp and well defined, but rather a broken zone, first of very coarse fragments of granite and gneiss, then of normal rhyolitic breccia with small fragments of granite and gneiss. The three lower levels have been run from 300 to 500 ft. north and west in this material, which is sometimes hard and jaspery and of dark-red color, but bleaches on exposure to the air. It is traversed by planes of movement, sometimes irregular and curving, but all having a general northwest strike. Beyond one of these planes is a dark bluish rock, supposed by the miners to be limestone because it effervesces freely with acid, but, on microscopic examination, found to be a decomposed basic eruptive, containing considerable calcite.

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In addition to the above metals, there was probably antimony, which had been proved qualitatively, in the mineral that was supposed at the mine to be hessite, but is probably either tetrahedrite or polybasite. Barium and alumina probably make up a part of the balance.

Of earthy minerals, the most common are barite, calcite, and quartz, the latter generally in the chalcedonic form. Fragments of country-rock are found in the vein, more or less rounded, and changed on the outer part into hornstone-like material, which, in turn, is coated with galena, barite, etc. Rounded cavities in the vein-material are often filled with a white powder, apparently an infiltrated decomposition-product of the rhyolitic tuff.

Water-Courses.—This mine has proved unusually dry for the region. In the upper part of the shaft the first considerable flows of water came in at 340, 390, and especially at 420 ft. This water, collected at the 500-ft. level, amounted to 250 gal. per minute, and was undoubtedly vadose or surface-water, and probably seeped in from the surrounding country. At 945 ft.

it had decreased to 65 gal. per minute, and below 1,000 ft. had practically ceased, the little water that was found being probably due to leakage along the shaft.

In the 1,450-ft. level what may be considered subterranean or deep waters were first struck. They were not very abundant, and were only slightly charged with gas. At one point on the south drift there was a slight deposit of tufa. A considerable flow was obtained from a vertical drill-hole sunk 300 ft. downward from this level.

In the 1,850-, 2,000-, and 2,100-ft. levels there are many small water-courses, from which proceeds a constant flow of water, not very great in aggregate amount, but highly charged with carbonic acid gas, so that there is a constant hissing, sputtering, and rumbling, and the water is ejected with such force as to go entirely across the drift at some points. These waters apparently ascend along fissures having a general parallelism with the ore-bearing fissure; but no water proceeds from the vein itself. They often come into the drifts through small cracks or cross-fissures at an angle with the direction of the main system. As they emerge into the air of the drift they deposit freely a calcareous tufa or sinter on the wall around the crack or orifice out of which they flow. This sinter is sometimes white, sometimes highly iron-stained; it has the texture and the peculiar wavy or ripple-marked surface characteristic of the sinters of the Yellowstone Park. In some places it takes a pisolitic form. Again its surface has a shiny glaze. It deposits very rapidly in some places. At one point on the 2,000-ft. level, which had been opened only four months, the water issuing from a minute vertical crack on the side of the drift had built out a little ridge of sinter over the crack, 1.5 in. from its base and less than 0.5 in. thick.

The water-courses are most active and abundant near the vein or on the line of its extension. On the 2,000-ft. level, where the vein splits to the northwest, the water comes in on all sides; and when the shaft was first opened, the escape of carbonic acid gas was so abundant at this point that it filled the lower 5 ft. of all the drifts on this level and the shaft below the level so that no light would burn, and the miners were obliged to abandon work until a blower could be put in operation to drive the gas out. Even now, a light is soon extinguished

if put at the bottom of the drift. The water-bearing fissures are mostly in the rhyolitic tuff, but a few are found in the Archæan, which shows evidence of faulting within itself, in slickensided clay seams and zones of brecciation. The water-bearing fissures decrease in number and in strength of flow as the distance from the line of the ore-bearing fissure increases. The abundant escape of gas is the most striking feature of these water-courses. Even where no water comes into the drift, one can often hear the bubbling and sputtering of the escaping gas in an adjoining fissure.

The temperature could not be accurately determined, but is about the same as that of the air in the drift at the 2,000-ft. level, viz., 80° F.

Analyses of Sinters.—Three typical specimens of sinter from the 2,000-ft. level were selected for analysis: one of the perfectly white, with very slight iron-stain; one white and brown (both showing the ripple-marked structure well); a third of the pisolitic sinter, strongly iron-stained. They were analyzed by W. F. Hillebrand, with the following results:

Analyses of Sinters from the 2,000-Ft. Level, Geyser Mine.

	White.	White and Brown.	Pisolitic Brown.
	Per Cent.	Per Cent.	Per Cent.
Silica and insoluble	0.08	0.10	0.17
CaO	53.11	52.60	52.59
CO_2	42.98	42.57	42.03
Fe_2O_3	0.20	1.08	1.82
Mn_2O_3 (Mn_3O_4?)	*a* 0.026	*a* 0.03	Undet.
SrO	0.17	0.26	0.22
MgO	1.50	1.39	1.01
K_2O	0.03	0.03	0.04
Na_2O	0.17	0.16	0.09
Li_2O	Trace.	Trace.	Trace.
H_2O below 110° C.	0.33	0.51	0.53
H_2O above 110° C.	0.88	0.72	0.87
SO_3	0.29	0.50	0.58
P_2O_5	Trace.	Trace.	Trace.
Cl	Faint trace.	Faint trace.	Faint trace.
Total	99.766	99.95	99.95

a Manganese was estimated on 34 g. The same samples showed also minute traces of lead, copper, nickel, cobalt, zinc, alumina, and a double trace of antimony.

On comparing these analyses with those of the waters which follow, it appears that, under the influence of free access of air,

with presumably reduced pressure and temperature, the precipitation has been mainly of carbonates of lime, iron, and manganese; of the alkalies, magnesia, and of other metals a relatively small proportion seemed to have been precipitated.

Analyses of Waters.—Carboys of water from the 500-ft. level, *i.e.*, surface or vadose waters, and of waters from the 2,000-ft. level were collected with great care by the foreman of the mine under the direction of C. H. Johnson and sent to Washington for analysis. Upon their arrival, there was found to be considerable sediment in each of the carboys, which had presumably been precipitated during the journey, since they had been filtered through cotton cloth when gathered. Mr. Hillebrand found evidence, however, that the filtering had not been complete, as some splinters of wood were found in the sediment, which casts some doubt on the analysis of the sediment.

In the 42.6 l. of vadose water of which the analysis is given below, there was a deep blackish-brown sediment, containing, however, no organic matter, which, after drying at 110° C., weighed 0.5592 g., and gave:

	Gram.
Ignition,	0.0642
HCl extract,	0.1588
Insoluble silica and silicates,	0.3362
Total,	0.5592

It was assumed that the silica and silicates must have been mechanically introduced, through want of sufficient precautions in filtering at the mine; and this portion of the sediment was not analyzed. Of the sediment in the carboy of deep water, however, the insoluble portion was analyzed, with the result given in the following tables. The total sediment in the carboy of deep water was 10.6602 g., of which 5.0134 g. was insoluble in dilute HCl (at 110° C.). The filtered vadose water had a slightly alkaline reaction and contained no organic matter. The results of analysis are given in the following tables [pp. 151 and 152]:

These tables present a remarkably complete series of actual analyses, representing:

1. The average contents of a vein-deposit of metallic minerals, rich in silver, lead, copper, and zinc, which was first found at over 1,800 ft. below the present surface.

Vadose Water from the Geyser Mine, 500-Ft. Level.

(W. F. Hillebrand, Analyst.)

In Sediment.		Soluble in HCl.		In Filtered Water.		
	Amounts Found.		Referred to Parts in 1,000,000 of Water.		Parts in 1,000,000.	Assumed Composition Before Sediment was Deposited.
	Gram.					
SiO_2	0.0012	SiO_2	Trace.	Cl	7.9	7.9
PbO	0.0010	Pb	Trace.	SO_4	43.2	43.2
CuO	0.0008	Cu	Trace.	CO_3 *a*	108.3	110.5
Fe_2O_3	0.0456	Fe	0.7	K	10.6	10.6
Al_2O_3, P_2O_5	0.0365	Al_2O_3, P_2O_5	0.8	Na	36.4	36.4
				Li	Trace.	Trace.
Mn_3O_4 *b*	0.0498	Mn	0.8	Ca	37.3	37.4
ZnO	0.0104	Zn	0.2	Mg	12.2	12.25
CaO	0.0096	Ca	0.1	Pb		Trace.
MgO	0.0039	Mg	0.05	Cu		Trace.
CO_2	(*c*)	CO_3 *d*	2.2	Mn		0.8
				Zn		0.2
	0.1588		4.85	Fe		0.7
				Al_2O_3, P_2O_5		0.8
				SiO_2		25.9
					281.8	286.65
				Free and semi-combined CO_2	38.8	37.2
					320.6	323.85
				Total CO_2	118.2	

a Calculated. *b* Assumed condition.

c Any traces of CO_2 present have been neglected.

d Calculated for the metals, as carbonates before deposition.

NOTE.—No tests for other possible constituents were made.

2. The contents of subterranean mine-waters taken at 2,000 ft. below the surface, and evidently coming from still greater depths, very highly charged with carbonic acid, and carrying small amounts of most of the metals that occur in the deposit; also the sinter deposited by these waters as they issue from the rock into the mine-drifts—that is, under ordinary atmospheric pressure.

3. The contents of atmospheric waters coming from the surface, which, in their downward course, had traversed rocks similar to those in which the first-named deposit is inclosed, and through which it may be assumed that metallic minerals similar to those in the deposit may be sparingly disseminated.

Deep Water from the Geyser Mine, 2,000-Ft. Level.

Specific Gravity 27° C. = 1.0036. (W. F. Hillebrand, Analyst.)

Composition of Sediment. (From 43.76 kg. of Water.)					Composition of Filtered Water.		Assumed Composition Before Sediment was Deposited.
Insoluble in Dilute HCl.		HCl Extract.				Parts in 1,000,000.	
Chiefly Clayey and Feldspathic Matter. Weight Dried at 110° C. 5.0134 g.		Amounts Found.	Referred to Parts in 1,000,000.				
	Per Cent.	Grams.					
SiO_2	54.07	0.0667	SiO_2	1.52	Cl	186.40	186.40
Al_2O_3 }		[a] 0.0461	Al_2O_3	1.06	Br and I	Traces.	Trace.
Fe_2O_3 }	29.70	0.2100	Fe	3.36	SO_4	161.70	161.70
TiO_2 }					PO_4	Trace.	Trace.
	A little (as $CaFl_2$?)	2.7921	Ca	45.57	NO_3	[f] 1.60	1.60
					B_4O_7	Trace.	Trace.
MgO	None.	0.0778	Mg	1.07	CO_3 [g]	1,437.26	1,513.44
K_2O	4.40 }	Not			Fl	None.	[h] Trace.
Na_2O	0.37 }	tested			K	198.00	198.00
SO_3	}	for.			Na	719.45	719.45
CO_2 [b]		2.3153	CO_3	[c] 76.18	Si	2.85	2.85
SrO		0.0440	Sr	0.85	Ca	108.84	146.41
BaO		None.	Ba	None.	Sr	1.10	1.95
Fl	A little.				Mg	176.60	177.67
PbO		0.0610	Pb	1.30	Pb	0.05	1.35
CuO		0.0011	Cu	0.02	Cu	Trace.	0.02
Mn_3O_4 [d]		0.0232	Mn	0.38	Mn	0.19	0.57
ZnO		0.0095	Zn	0.17	Zn	0.17	0.34
Ignition	9.47	(e)		(e)	Fe	0.14	3.50
					Al_2O_3	None.	[i] 1.06
					SiO_2	22.90	24.42
					Org. mat.	Not est.	Not est.
						3,009.25	3,140.73
	98.01	5.6468		131.48	Total CO_2	2,472.60	2,528.45

[a] Perhaps derived from the mechanically-included minerals of the sediment. Contains a little P_2O_5.

[b] The sediment was largely incrusted on the glass of the carboy and could only be removed by acid; hence the CO_2 was caculated for PbO, ZnO, SrO, CaO, MgO, as normal carbonates.

[c] This value includes the CO_3 needed by Fe, Mn and Cu, as well as the metals named in the preceding notes.

[d] Assumed condition; perhaps partly as $MnCO_3$.

[e] Organic matter not estimated.

[f] Approximation, not a maximum.

[g] Calculated for normal carbonates.

[h] The fluorine of the insoluble part of the sediment is probably to be credited to the water.

[i] Possibly from the insoluble sediment.

From these analyses it is possible to apply a practical test to some of the assumed theories of ore-deposition.

Source of Solid Constituents in the Waters.—In the first place, in comparing the contents of the vadose and deep waters, it is seen that though the latter contain about 20 times as much

dissolved matter as the former, the relative proportions of the principal constituents are sufficiently alike to permit the assumption that they have been derived from a similar source; and this source, in the case of the surface-waters, which should have been practically pure when they entered the rocks, must have been the material of the various rocks through which they have passed in reaching a depth of 500 ft. below the surface. In making this comparison, one must bear in mind that the deep waters had already deposited the greater part of their lime as sinter before they were analyzed; hence, while the vadose waters contain three times as much lime as magnesia, in the analysis of the deep waters lime is to magnesia in the proportion of only 4 to 5.

The alkalies appear in the same relative proportions in each case, though the aggregate amount of the two constituents is proportionately less in the vadose than in deep waters.

Iron and manganese are in nearly equal amounts in the vadose waters, the latter slightly predominating, whereas in the deep waters iron is in a hundred-fold greater relative amount. This might be explained by the relatively larger amount of manganese oxides present in the surface-rocks. It has often been noted by the writer that manganese oxides are generally present in much larger proportion in the oxidized portions of ore-bodies than below the zone of oxidation, which may be due to their forming, in contact with atmospheric agents, less soluble salts than do the iron oxides.

The other metals are in such small proportions in either case that one cannot reason from their relative amounts; and it is not surprising that most of them could not be detected in the vadose waters.

Such constituents as fluorine, boric and nitric acids, strontium, and barium are characteristic of deep sources, but they also might have been present in the vadose waters without being detected in the small amount of solid constituents available for analysis.

The greatest apparent discrepancy is the ten-fold greater proportion of silica in vadose than in deep waters; but this is likely to have arisen from excess of CO_2 in deep waters which would throw down silica in solution, or from the uncertainty in determining what part of the solid material in the waters was due to mechanical admixture, and hence might be neglected.

In the deep waters chlorine and sulphuric acid are present in about equal proportions, and carbonic acid is greatly in excess of both combined. In the vadose waters, while carbonic acid is still in excess, sulphuric acid appears in relatively greater, and chlorine in relatively smaller, proportion than in the deep waters. In what manner they would combine with the several bases in either case it is of course impossible to say definitely.

The deductions which the writer draws from these considerations are:

1. That inasmuch as the surface-waters must evidently have derived the substances they contain in solution from the rocks through which they have passed in seeping downward, it is fair to assume that, in like manner, the deep waters have obtained their constituents (in great part, at any rate) from surrounding rocks, and not necessarily at very great distances from where they now issue, since through higher temperature and greater acid contents they would probably have been more active solvents than the surface-waters.

2. On the other hand, the great excess of carbonic acid in the deep waters, combined with the presence of fluorine, boric acid, and chlorine in considerable amount, points to a source where chemical decomposition is actively going on, which might readily be supposed to be a body of still uncooled igneous rocks, which surface-waters had reached, and from which they were sent back towards the surface again along the present lines of fissuring. Although the deep waters contain most of the metals found in the vein-deposit of the Geyser mine, it is not easy to conceive how the metallic sulphides of that deposit could have been derived from waters of such chemical composition as these; and it seems more reasonable to assume that the vein-minerals were deposited by earlier waters of somewhat different composition, carrying more barium and silica, and characterized by sulphuretted hydrogen rather than by carbonic acid.

3. The conditions here indicated seem to negative the prevalent belief that a decrease of temperature and pressure is the principal determining cause of the precipitation of vein-minerals from ascending solutions. In the earlier deposits abundant precipitation ceased before the marked decrease of temperature and pressure that accompanies an approach to the actual rock-

surface was reached; and in the modern mine-openings, where present ascending waters have been artificially cooled and relieved from pressure, the abundant deposit has been, like that of thermal springs at the surface, mainly of carbonate of lime and oxide of iron, and contains only faint traces of the other vein-materials that make up the bulk of the neighboring vein-deposits.

4. It might be assumed that the surface-deposits of chloride of silver and oxides of manganese and iron which are thinly and irregularly disseminated through the rhyolite near the actual surface, were precipitated from the carbonated waters at a time when they reached the present surface, the oxides having been originally carbonates, and the silver chloride having been deposited as such, and that these deposits are therefore a later phase of ore-deposition than the vein-minerals. A certain color of probability is lent to this hypothesis by the fact noted by Mr. Johnson, superintendent of the Geyser mine, that there is evidence of an escape of warm air or gas through holes at the surface, which in cold weather is visible as steam, along a zone about 100 ft. wide, running east and west through the Geyser shaft-house. Moreover, fluorite and barite are said to have occurred, associated as gangue-minerals with chloride of silver, in the Silver Bar (formerly Kate) mine.

On the other hand, all our evidence goes to show that the chlorides and oxides pass into sulphides at short distances below the surface, and that here, as in other deposits, the chloride of silver is a secondary alteration by atmospheric agents of an original sulphide. It appears more probable, therefore, that all the metallic minerals of the plateau were formed under the same conditions and during the same general phase of ore-deposition. That they are so irregularly disseminated is probably due to physical rather than to chemical causes. The rhyolitic tuff which forms the main country-rock is so poorly consolidated, and of so plastic a nature, that fracture-planes are less continuous and less open in it than in harder and more rigid rocks. Moreover, the natural planes of division, the bedding-planes, are horizontal rather than vertical. Hence there have been no well-defined and continuous water-channels traversing the whole thickness of the mass, but the ascending solutions, after leaving the vicinity of the bounding-walls of the

harder Archæan rocks, have been obliged to follow devious courses along minute cracks and fissures that were not continuous. Thus, comparatively small amounts of these solutions have reached the upper lavas, and their load has been deposited as thin films in the joints or minute cracks of the rocks. The fact that, at the present time, the descending surface-waters penetrate the mass to so moderate a depth is an argument in favor of this view.

It is probable that the present vein-fissure will soon reach and pass into the Archæan wall-rock, in which it may widen out. It is very uncertain whether, in this case, the ore will continue to be as rich as it has been; for a change in wall-rock is generally accompanied by a change in the character of the ore. These points will soon be settled, however, by actual development, as the workings of the Geyser mine follow the present vein in depth.

General Conclusions.

Forms of the Ore-Bodies.—The preceding pages have been mainly devoted to the description of the Geyser mine in the immediate vicinity of Silver Cliff. Other important deposits within this area, and in the surrounding region, have not been mentioned, because, owing to the irregular and disconnected manner in which they have been worked, it has been impossible to obtain any detailed information with regard to them. With but few exceptions, these deposits belong to the type of the Humboldt-Pocahontas vein; that is, they are vein-deposits on fault-planes in some of the many varieties of igneous rocks that outcrop in the region. They are, in general, rather narrow fissures, which do not bear evidence of having at any time constituted large open spaces, but in which the ore-bearing solutions have deposited their contents by first filling the interstices between the sheets of sheared and banded country-rock and afterwards partly replacing these sheets or bands by vein-materials. The ore in these cases is generally confined to the fault-fissure, and the deposits may be characterized as well-defined vein-deposits or true fissure-veins.

The mines of the Silver Cliff plateau show a different type of deposit, but, in the opinion of the writer, the essential differences lie rather in the form of the ore-channels than in the

character of the ore-bearing solutions. From Mr. Cross's description of the Democrat and Ben Eaton mines, in the central rhyolitic area, these deposits seem to constitute an intermediate stage between the two types. These mines occur on the south point of Democratic ridge, known as Indian Castle. This is a rounded eruptive channel of rhyolite, in which the rock is massive, brecciated, or spherulitic, as the case may be. There are indications that there have been several eruptions. It has since been much altered, and the alteration-products vary from hard quartzite-like material to softer material, resulting from the kaolinization of inter-spherulitic glass. Trachyte dikes run both north and south and east and west through the mountain, and their decomposition-product is usually soft. The ore-bearing fissures run north and south, with a steep eastern dip, through both rhyolite and trachyte. The ore-solutions followed these fissures primarily, but found the softened spherulitic glass and certain brecciated zones also very good channels. The ore is now found in these seams or fissures, but all soft kaolinized parts are likely to be impregnated. The main ore-body was an oval chimney, of varying size, in soft matter, which is connected with a fissure at tunnel-level. From one part, on stoping upward, a soft yellow mud flowed out, which was found to carry 40 oz. of silver and $14 in gold to the ton. For the most part, the solid masses of ore are less than 1 in. thick.

It has already been suggested, in the case of the deposits on the Silver Cliff plateau, that the fact that the surface-deposits are not in the form of fissure-veins, as they are found at the bottom of the Geyser shaft, is due to physical causes which have not permitted the formation of long continuous water-channels along fissures. In this case similar irregularities have been produced by chemical causes; but it has been the physical effect—the production of channels of freer flow, through the decomposition of the rock—that has led the ore-depositing currents to leave the regular fissures.

The deposits in the Archæan rocks on the borders of the eruptive region are likewise unusually irregular in form; and, in most of the observed cases, this irregularity may be ascribed to a combination of chemical decomposition with dynamic fracturing of the rocks; that is, while the ore-channels have been

primarily determined by the dynamic movements that produce the ordinary rock-fractures, vein-fissures, and brecciated zones, on which ore-bodies are generally deposited, their course has been varied, or they have received unusual forms as the result of the energetic dissolving or decomposing action of heated solutions that traversed them during the closing phases of volcanic action in the region. This supposes a prolonged alteration and decomposition of the rocks along the water-channels before the actual deposition of metallic minerals. In some of the observed cases, there are fairly well defined fissure-veins in the Archæan rocks; but more commonly, in this region, the ore-deposition appears to have taken place along a zone of decomposed rock, which zone was undoubtedly determined in the beginning by dynamic action. The ore-deposition along such zones, as might be expected, has been more irregularly spaced and less concentrated than would have been the case in a fissure which had not been thus enlarged by chemical decomposition. The Bull-Domingo ore-body is apparently an extreme type of such a form.

Whether it be or be not admitted that the boulder-filled channel of the Bull-Domingo represents the neck of an ancient crater of explosion, the Bassick ore-body is unique in the evidence it affords of a direct connection with volcanic agencies; and in the determination of its form dynamic agencies have apparently played a very subordinate part.

Cripple Creek Deposits Compared.—It is interesting to contrast the deposits of this region with those of the now famous Cripple Creek district, which lies in a closely analogous geological position, 40 miles to the northward, and which presents in its geological structure so many points of resemblance. There, as here, the main ore-deposition has taken place in and around a central volcanic focus, where a series of comparatively recent igneous rocks have broken through an older series of pre-Cambrian crystalline rocks. There, as here, the principal deposition has taken place along a system of fracture-planes, traversing both the eruptives and the underlying crystalline complex, and, while not strictly confined to the eruptives, it has been, so far as present developments show, more abundant in the former than in the latter.

In the Cripple Creek region there is one principal and pre-

dominant system of mineralized fractures, running about north and south. In this district a system running north and south or a little west of north is apparently the more frequent, but there are also abundant fractures running east and west, and others quartering between the two. The geological history of this region has been more complicated; there have been a greater number of successive eruptions; and it is probably in consequence of this fact that the fracture-systems are more varied and complicated.

Mineralogically the contrast is greater. In Cripple Creek the important metal is gold, deposited mainly in the form of telluride, and the characteristic earthy mineral associated with it is fluorite. Here, gold as telluride occurs in certain parts of the district, and fluorite is sparingly found; but the greater part of the valuable minerals are silver-minerals, in their usual association with sulphides of lead, zinc, and iron, and with barite as the leading gangue-mineral. They differ from the ordinary deposits of this class mainly in their greater average richness.

Source of the Metallic Minerals.—While it is possible, by careful study of the geological and mineralogical conditions of a series of ore-deposits, to find valid reasons why the ore-bearing solutions deposited their load in certain forms and certain localities, and while reasonable deductions may be made as to the probable direction from which these solutions came, the question as to the source from which the solvents derived the materials which they have thus deposited in the form of ore-bodies is one that trenches somewhat upon the domain of pure speculation. Yet, even here, there are many facts of geological observation that have a distinct bearing, one way or the other, upon the various speculative views that have been put forth by geologists.

The general views of the writer upon this question, as already expressed in earlier publications, are: that the heavy metals have probably been brought up from the interior of the earth within the magmas of igneous rocks, and that by some process of differentiation not yet completely understood, either previous to or during the process of cooling and consolidation, they have been concentrated within certain bodies or parts of bodies of eruptive rocks; and, further, that ore-bodies, as found at the present day, are the result of a concentration (perhaps many times repeated) of the materials thus brought up, which are in

all probability very finely disseminated through the present rock-masses or combined in minute amounts in the more common basic minerals. This seems a more rational hypothesis, and one more in accordance with modern scientific practice, than to content oneself with assuming simply that the ascending waters came charged with metallic minerals from the bathysphere, meaning thereby a region in the interior of the earth which is richer in heavy metals than any part of the earth's crust that comes under our observation; for this simple assumption affords no explanation why metallic minerals are concentrated in one part of the earth's crust and not in another, and it supposes a free flow of waters at greater depths than in our present state of knowledge of terrestrial physics it is considered possible that channels which would admit of a flow of water through them could remain open.

Furthermore, the writer's hypothesis admits of a practical test, which is impossible in the other case. If the vein-materials are found to form a constituent part, even in minute traces, of comparatively fresh and unaltered country-rocks in a given ore-bearing region, and at such distances from any water-channels as to render it improbable that these materials could have been brought in through these channels, it is reasonable to assume that these or similar rocks have been permeated by the waters from which the known ore-deposits were precipitated, and that from them they derived their contained vein-materials. For this reason a series of careful tests of selected country-rock for possible contents in the precious metals was carried on under the direction of the writer at the laboratory of the U. S. Geological Survey in Denver. Since the office at Denver was broken up, it has not been possible to continue these tests, owing to want of proper facilities in the Washington laboratory.

Such tests of the rocks from this district as were completed (unfortunately very few in number) are given below.

The five assays for silver were made upon 4 assay-tons of each sample, and blank assays of a like amount of the lead-flux were simultaneously made, the silver-content of the flux being deducted from that found by the rock-assay.

In the case of the black granite from the Blue mountains, another portion of the rock was pulverized and the constituent minerals were separated by the Sonstadt solution. The bi-

silicates in this case were found, as shown below, to contain both silver and lead; but no silver was found in either quartz or feldspar. The assays of Custer county country-rock for silver, by L. G. Eakins, analyst, were:

Rock.	Locality.	Silver per Ton.
		Ounce.
Trachyte	600 ft. southwest of Humboldt shaft	0.007
Trachyte	Summit of Game ridge	None.
Rosita breccia	South of Game ridge	None.
Rosita breccia	South of Game ridge	None.
Fairview diorite	Mount Fairview	0.01
Tyndall andesite	Northeast spur of Mount Tyndall	None.
Rhyolite	Top of Round mountain	0.402
Red granite	Near Haskell's ranch	0.005
Black granite	Blue mountains	0.025
Bisilicates of black granite (0.045 per cent. lead)		0.04

It thus appears that five out of nine of the rocks tested contain appreciable amounts of silver; and that in one of these rocks both silver and lead were found to be present in combination with other bases in the bisilicates. It seems, therefore, probable that not only the recent eruptives, but the older granites through which the ascending solutions must have passed, contain enough of the precious metals, and, it may be assumed also, of the other vein-materials, to furnish, in the long time that is accorded to the accomplishment of most geological phenomena, sufficient material for the formation of existing ore-bodies. The analysis of the vadose waters in the Geyser mine has demonstrated the capability possessed by even cold surface-waters of taking up such materials in their passage through the rocks. The subterranean waters that were circulating here at the time of the formation of the ore-deposits must have been much more energetic solvents, being heated by contact with the cooling masses of igneous rocks, and probably deriving a certain amount of active and energetic mineralizing-agents, such as fluorine, chlorine, etc., from these igneous masses at the time of contact. Hence it is fair to assume that the vein-materials in this region were originally derived from both recent and ancient eruptive rocks—a conclusion similar to that arrived at by Mr. Penrose, from his more exhaustive study, for the ore-deposits of Cripple Creek.

No. 8.

The Genesis of Certain Auriferous Lodes.

BY JOHN R. DON, OTAGO, NEW ZEALAND.

(Chicago Meeting, February, 1897. *Trans.*, xxvii., 564. Here reprinted in part only.)

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CHAPTER V.—THE EXAMINATION OF VARIOUS CONSTITUENTS OF CRYSTALLINE AND ERUPTIVE ROCKS FOR GOLD AND SILVER.

In the South Island of New Zealand an unusually favorable opportunity is offered for the analysis of the older crystalline rocks, underlying the sedimentary rocks which form the "country" of the gold-deposits. The Manipori formation of this island, comprising the greater part of the mountainous district west of lakes Manipori and Te Anau, in Otago, consists of an enormous thickness (estimated by Professor Hutton[1] at 160,000 ft.) of crystalline schists, gneiss, syenite, and syenitic gneiss, with associated masses of granite; the whole forming the most picturesque part of New Zealand. The famous West Coast sounds occur in this formation. No paying auriferous lodes have been discovered in it; and for this reason an examination of the rocks is specially interesting here. Stelzner, Posepny, and others, who have criticised the conclusions of Sandberger, have laid great stress on the fact that all the silicates analyzed by him were taken from the vicinity of ore-bodies containing those heavy metals which he notes as occurring in the silicates of the country-rock; their contention being that these metals, supposed to occur as silicates in gneiss and other crystalline rocks, were really contained as sulphides, and were therefore impregnations from the neighboring ore-bodies. The same objection, whatever be its weight, might be urged with equal justice against Mr. Becker's derivation of the mercury and gold of the lodes of the Pacific Coast from the granite underlying their country-rock. In the case of the

[1] *Geology of Otago*, by Hutton and Ulrich, p. 28.

Manipori formation, just mentioned, such criticism could hardly be made, as no auriferous lodes have been found within many miles of the district from which samples were taken for the present investigation.

In the South Island also, samples were taken from the granite abutting on the Carboniferous strata near Reefton, which latter are the chief carriers of auriferous lodes in the western part of the island.

Other samples of granite were collected from various parts of Westland and Nelson, as far north as the granite-quarries of Cape Foulwind.

Selwyn has pointed out[2] that the auriferous Silurian rocks of Victoria probably rest everywhere on granite; and this conclusion has been supported by the later observations of Murray[3] and others. This underlying granite has not been reached in any of the mines working in the stratified rocks about it; but it is exposed at the surface in many parts of the colony, both near to gold-bearing areas and distant from them. Numerous samples of it were taken for this investigation.[4]

The study of the country-rock from Gympie and Charters Towers, Queensland, gave a good opportunity for the analysis of silicates from crystalline igneous rocks. In the case of Charters Towers, the whole country-rock (locally termed granite) is quartz-diorite, with a little accessory mica; while at Gympie a thick sheet of diorite-aphanite (locally termed greenstone), containing a large percentage of carbonate of lime, is interbedded with the shales which bound the auriferous reefs, these kindly shales occurring both above and below it. Messrs. Alfred Lord and R. Steele, of Gympie, have furnished samples of the "greenstone."

Sandberger's results having been criticised on the ground that all the rocks he analyzed contained sulphides, and Posepny[5] having urged the same objection to Becker's conclusions

[2] *Geology and Physical Geography of Victoria*, by A. R. C. Selwyn and G. F. H. Ulrich.

[3] *Geology and Physical Geography of Victoria*, by A. R. F. Murray (1887).

[4] In New South Wales, granite forms the country-rock of a number of auriferous lodes; and it is much to be desired that some investigator on the spot would take up this inquiry. The present paper contains no analyses of New South Wales granite.

[5] The Genesis of Ore-Deposits, *Trans.*, xxiii., 282 (1893).

in the case of the Comstock lode, this point was carefully guarded. In every instance (even though an examination of a hand-specimen showed no sulphides), an analysis of the rock was first made, to determine whether sulphides were present; and whenever such was the case, the sulphides were isolated by panning, and separately assayed for gold and silver; but *when sulphides were thus found, no separation of the other crystalline constituents of the rock was made.*

It was deemed necessary to isolate and examine the following minerals: (1) *mica* and (2) *hornblende*, because to these Sandberger traces the silver and gold of many European lodes; (3) the *pyroxenes* of the later eruptives, because Becker traces the gold and silver of the Comstock to the augite of the diabase, and both Hutton and Park (already cited) are inclined to refer the gold and silver of the Thames district, N. Z., to the pyroxenes of the andesite;[6] and (4) *magnetite*, because of Professor Hutton's remark:[7]

"I would suggest that, as part, at least, of the pyrites has been formed from magnetite, the gold may have been originally in the magnetite, and have been released during the formation of the pyrites. I do not think that this has been the case, *but it is a point worthy of investigation by the chemist.* The pyrites is, no doubt, a secondary mineral, formed in the rock after consolidation; and if it should turn out to be generally auriferous, we must suppose either that the gold came from below with the sulphur, or that its source is the titaniferous magnetite which is one of the original constituents of the rocks."

Isolation of Minerals.

The crystalline rocks examined comprised: (1) those in which certain minerals were distributed in large crystals or arranged in folia, so that clean samples could be picked out by hand; and (2) those from which the various minerals had to be separated by means of a liquid of high specific gravity.

The first class included many samples from the gneiss, syenite, and granite of the Manipori formation, N. Z., from which the separation of mica and hornblende was specially easy. In various parts of this formation mica veins are abundant. It

[6] Professor Hutton says on this point (*op. cit.*, p. 272): "If, therefore, we assume that the pyroxenes of our volcanic rocks contain gold and silver, that the conditions necessary for dissolving them rarely obtain, but that one of the exceptions has been in the Hauraki [Thames] gold-fields, we have a hypothesis which will, I think, explain most of the facts."

[7] *Op. cit.*, p. 271.

was sometimes possible to pick in a few minutes 2 or 3 lb. of clean mica in plates up to 2 or 3 in. square. The syenite and syenitic gneiss often contain bands of almost pure hornblende, quite an inch thick, permitting a similarly easy isolation. Finally, magnetite can, of course, be easily separated from any rock in which it occurs.

The treatment of the second class, comprising many of the rocks examined, may require some explanation.

The separation of minerals from rocks by means of heavy solutions is extremely tedious, and it is therefore desirable to reduce the quantity of the rock to be operated upon if this can be done without material loss of the mineral to be isolated. As all crystalline rocks contain a large percentage of material below 3 in specific gravity, which can be effectively removed by panning, each sample was concentrated first by panning to get rid of quartz, feldspar, and other specifically light materials. This procedure would, of course, be inadmissible if the object had been to determine accurately the gold and silver *per ton of the rock examined;* but the purpose in each case being simply to get as large a quantity as possible of a given mineral, and to get that sample approximately pure, this preliminary crude concentration seemed to be unobjectionable.

As an illustration, the following record of the process, as applied in one instance (Sample 7, Table I. [Table XVIII. of original paper]), is here given. With suitable modifications, this method was followed in all similar cases:

Sample of Syenite.

1. The sample was roughly broken and examined with a good lens, but no sulphides were discovered. A chemical analysis of 10 g. of the sample also showed that sulphides were absent.

2. A portion of 500 g., pulverized so as to pass a No. 30 sieve, was reduced by careful panning to 217 g., of which 58 g. was removed by a weak magnet. The portion thus removed proved, under the microscope, not to be pure magnetite, but to contain a good proportion of hornblende and feldspar (chiefly orthoclase) grains, probably drawn to the magnet by small adhering particles of magnetite.

3. The 159 g. not attracted by the magnet consisted chiefly of hornblende and feldspar, with a little mica (biotite) and quartz. This powder was introduced into an apparatus modeled on Thoulet's, but made much larger, to save time. The heavy liquid used was Sonstadt's: mercuric iodide, dissolved in excess of potassic iodide, and having 3.175 sp. gr.

On exhausting the air from the apparatus, 77.5 g. of practically-pure hornblende fell to the bottom of the liquid. A dilution of this liquid to 2.95 sp. gr. was followed by the precipitation of 35.5 g. more—also nearly-pure hornblende.

The total of 113 g., reckoned as hornblende, was finely powdered and assayed with pure litharge. No trace of gold or silver was obtained.

4. The 58 g. removed by the magnet was similarly powdered and assayed, with the same result.

Sonstadt's solution is cheap and easily prepared, but has the great disadvantage of being extremely corrosive. Even with the greatest care, it was found almost impossible for the operator to avoid burning his fingers. Hence, in a number of instances Klein's solution of boro-tungstate of cadmium was employed. This has another advantage over Sonstadt's solution, namely, that when a partial separation of hornblende from augite is desired, the greater part of the hornblende can be kept from sinking in the liquid by using the latter in the concentrated state.[8]

The results of the analysis of minerals separated from 47 samples of rock are given in Table I. On this table the following additional notes are presented:

1. Sample 17 represents a rock of peculiar occurrence, occupying a narrow strip in an area of Tertiary trachyte at Portobello, on the east coast of the Otago peninsula. Samples taken short distances apart vary much in character; but, on the whole, the rock may be classed as a diorite. Gold was said to have been found *in the rock*, up to 0.5 oz. to the ton. If this were the case, such an occurrence of gold would have been, so far as the writer knows, unique.

Of the three samples chosen, one (No. 17) contained pyrite, and this pyrite was—but the rock itself was not—auriferous. The occurrence of auriferous pyrite in such an area (of recent volcanic rocks) is most unusual, and Professor Ulrich, Director of the Otago School of Mines,[9] who has examined the locality and studied rock-sections from it, thinks that this diorite rock probably underlies the basic volcanics which form the rest of

[8] It was found impossible to separate augite from hornblende completely by the use of heavy liquids; but since no gold or silver was found in either, this fact did not affect the practical results of this investigation. The same remark applies more or less to all the minerals thus isolated for analysis. The writer knows of no method which will perfectly isolate considerable quantities of one mineral from other minerals not widely removed in specific gravity. In Table I., therefore, the terms "hornblende," "augite," etc., simply designate the greatest part of the mineral samples to which they are applied.

[9] I desire at this point to express my grateful thanks to our respected chief, Professor Ulrich, for much kind encouragement and practical assistance.

TABLE I. (*Table XVIII. of original paper*).—*Analyses of Various Minerals Isolated from the Older Crystalline and Newer Eruptive Rocks of New Zealand, Victoria, and Queensland.*

A. ROCKS OF NEW ZEALAND.

Sample.	Locality.	Weight Taken.	Mineral Isolated.	Weight of Mineral Isolated.	Method of Separation.	Sulphides.	Results.
		Gm.		Gm.			
1	From the "Staircase," on the Sutherland Falls road, Milford sound, W. coast of Otago.	200	Mica.	200	Picked by hand.	None.	No gold or silver.
2	Do	150	Mica.	150	Do.	None.	Do.
3	Clinton gorge, N. W. of Lake Te Anau, on Milford sound road.	150	Mica.	150	Do.	None.	Do.
4	Roaring creek, Arthur River valley, near Milford sound.	100	Mica.	100	Do.	None.	Do.
5	On the track between Milford sound and Lake Ada, W. coast of Otago.	100	Mica.	100	Do.	None.	Do.
6	Dusky sound, W. coast of Otago.	.....	Hornblende.	.....	Do.	See note below.	See note below.
7	Do	500	Hornblende.	113	Sonstadt's solution.	None.	No gold or silver.
8	Milford sound, W. coast of Otago.	100	Hornblende.	100	Picked by hand.	None.	Do.
9	Preservation inlet, W. coast of Otago.	100	Hornblende.	100	Do.	None.	Do.
10	West Jacket Arm, W. coast of Otago.	140	Hornblende.	140	Do.	None.	Do.
11	George sound, W. coast of Otago.	500	.....	.....	.....	See note below.	See note below.
12	Do	200	Hornblende.	200	Picked by hand.	None.	No gold or silver.
13	Do	1,000	Hornblende.	.....	Do.	See note below.	See note below.
14	Skipper's creek, central Otago.	.....	Magnetite.	250	Magnet.	None.	No gold or silver.
15	Shotover river, central Otago.	.....	Magnetite.	150	Magnet.	None.	Do.
16	Do	.....	Magnetite.	180	Magnet.	None.	Do.
17	Portobello, Otago Peninsula, near Dunedin.	.....	.....	.....	.....	See note below.	See note below.
18	Do	500	.....	Hornblende, 57 Mica, 43	Sonstadt's solution.	None.	No gold or silver.
19	Do	500	.....	Biotite, 38 Hornblende, 26	Sonstadt's solution.	None.	Do.
20	Near Dunedin	.....	Magnetite.	60	Magnet.	None.	Do.
21	Water of Leith, near Dunedin	.....	Hornblende, 2.8 to 3 Augite, 3 to 3.2	16 25	Klein's solution.	None.	Do.
22	Near Oamaru, Otago.	.....	Magnetite.	80	Magnet.	None.	Do.
23	Cape Foulwind, W. coast of Nelson.	.....	Mica.	200	Picked by hand.	None.	Do.
24	Inangahua river, Reefton.	500	Mica.	84	Klein's solution.	None.	Do.
25	Cape Foulwind quarries, W. coast of Nelson, N. Z.	500	Mica.	43	Sonstadt's solution.	None.	Do.
26	Rangitoto, Westland, N. Z.	.....	.....	.....	Klein's solution.	See note below.	See note below.
27	Bed of Hokitika river, Westland, N. Z.	500	Mica.	48	Do.	None.	No gold or silver.
28	Bligh sound, W. coast Otago.	500	Mica.	61	Do.	None.	Do.
29	Moanataiari tunnel, Thames district	1,000	Pyroxenes of sp. gr. 2.9 to 3.2	73	Do.	None.	Do.
30	Do	1,000	Hornblende and chlorite between sp. gr. 2.8 and 3.1.	56	Do.	None.	Do.

TABLE I.—*A. Rocks of New Zealand.—Continued.*

Sample.	Locality.	Weight Taken.	Mineral Isolated.	Weight of Mineral Isolated.	Method of Separation	Sulphides.	Results.
		Gm.		Gm.			
31...	Waitekauri creek Thames district.	1,000	Hornblende and chlorite between sp. gr. 2.8 and 3.1.	65	Klein's solution.	None.	No gold or silver.
32...	Moanataiari tunnel, Thames district.	1,000	Pyroxen's between sp. gr. 2.9 and 3.2.	43	Do.	None.	Do.
33...	Fame and Fortune G. M. Co., Thames.	1,000	Do.	84	Do.	None.	Do.
34...	Do	500	Do.	27	Do.	None.	Do.
	B. ROCKS OF VICTORIA.						
35...	900-ft. level, Long Tunnel G. M. Co.	1,000	Hornblende.	73	Klein's solution.	None.	No gold or silver.
36...	Thomson river, near Walhalla, Gippsland, Vict.	1,000	.....	.....	.....	See note below.	See note below.
37...	Do	1,000	Hornblende.	38	Klein's solution.	None.	No gold or silver.
38...	Big hill, Bendigo, near the Silurian boundary.	.....	Hornblende.	.....	.....	See note below.	See note below.
39...	Do	500	Mica.	53	Klein's solution.	None.	No gold or silver.
40...	Do	500	Mica.	84	Do.	None.	Do.
41...	From Gabo Island, S. E. of Vict., used as a building stone in Melbourne.	1,000	Hornblende.	96	Do.	None.	Do.
42...	Ballarat East, Victoria.	.....	Magnetite.	50	Magnet.	None.	Do.
43...	Sunbury, near Melbourne, Victoria.	.....	Magnetite.	40	Magnet.	None.	Do.
	C. ROCKS OF QUEENSLAND.						
44...	The 1,070-ft. level, Brilliant and St. George G. M. Co., Charters Towers, Queensland.	500	Sp. gr. 2.75 to 3 (biotite). Sp. gr. 3 to 3.2 (hornblende)	21 50	Klein's solution.	None.	No gold or silver.
45...	Do	500	Sp. gr. 2.75 to 3 (biotite). Sp. gr. 3 to 3.2 (hornblende)	47 40	Klein's solution.	None.	Do.
46...	The 950-ft. level of the No. 5 North Phœnix G. M. Co., Gympie.	1,000	.....	36	.....	See note below.	See note below.
47...	Do	1,000	.....	25	.....	Do.	Do.

1, 2. Gneiss, containing veins of mica, about 0.5 in. wide, mixed with quartz. Several pounds' weight of mica were easily obtained.

3. Granite, with muscovite in large plates, easily picked out of sample.

4, 5. Gneiss; contained veins of muscovite, from which pieces 2 in. square were easily picked out.

6. Syenitic gneiss, consisting of quartz, feldspar, and hornblende, with a little biotite, the hornblende in a seam about 2 in. wide. Pyrrhotite and chalcopyrite, with minute specks of native copper, associated with the hornblende; 500 g. of the rock gave 53 g. of sulphides, mostly pyrrhotite, which contained 0.0053 of silver.

7. Syenite.

8. Syenitic gneiss. A vein of hornblende about 2 in. wide occupied the greater part of the sample analyzed.

9, 10. Syenite-porphyry, showing large patches and crystals of hornblende.

11. Syenitic gneiss, consisting of quartz, feldspar, and biotite, with patches of hornblende. Sample showed pyrrhotite and pyrite; 500 g. gave 18.56 g. of these minerals chiefly, but no gold or silver was found.

12. "Granite," a rock containing pink feldspar, quartz, muscovite, and bands of hornblende.
13. "Granite," a rock containing orthoclase, quartz, muscovite, and hornblende in veins; 1,000 g. gave 12.18 g. pyrrhotite and arsenopyrite, which yielded no gold or silver.
14. Chlorite-schist, containing numerous octahedral crystals of magnetite.
15. Hornblende-schist, containing numerous octahedral crystals of magnetite.
16. Heavy "black sand," result of erosion of mica-schist.
17. "Diorite," consisting of triclinic feldspar, hornblende, biotite, magnetite, and a little quartz; 1,000 g. gave 4.934 g. of pyrite, containing 0.037 grain of gold and 0.0041 grain of silver.
18, 19. Diorite, like No. 17.
20. Phonolite.
21. Basalt, very much decomposed, with large, undecomposed crystals of augite and hornblende.
22. Hard, solid basalt, from a quarry.
23. Gneiss-granite, with large folia of mica, easily picked out of sample.
24, 25. Fine-grained granite.
26. Granite, with a pyritous vein; 1,000 g. gave 28.92 g. of arsenopyrite and pyrrhotite, with a little galena, and this yielded 0.0032 grain of gold and 0.0019 grain of silver.
27. Granite.
28. Gneiss.
29. Nepheline-andesite, hard, very little decomposed.
30. Hard blue hornblende-andesite.
31. Hornblende-andesite, slightly altered.
32. Augite-andesite, with much chlorite.
33, 34. Hard blue unaltered augite-andesite.
35. "Diorite" dike, near auriferous reef, Walhalla, Gippsland, Victoria.
36. "Diorite, associated with copper-lode. Showed chalcopyrite, of which there were obtained from 1,000 g. of the rock 16.48 g. (with a small quantity of bournonite), yielding 0.407 grain of silver and no gold.
37. "Diorite," like No. 36.
38. Syenitic granite (quartz, orthoclase, and muscovite, with large crystals of hornblende); 1,000 g. gave 16.03 g. of pyrite, yielding neither gold nor silver.
39. Syenitic granite, like No. 38.
40. Granite.
41. Syenite.
42. Very dense basalt, overlying auriferous slates.
43. Vesicular basalt.
44, 45. Quartz-mica diorite (tonalite: the "granite" of Charters Towers).
46. Diorite-aphanite, with much carbonate of lime (calc-aphanite); a very much altered rock; effervesces strongly with acid (the "greenstone" of the Gympie field); it contains pyrite and sphalerite in small quantities; 1,000 g. gave 8.42 g. of pyrite, yielding no gold or silver.
47. Diorite-aphanite, like No. 46; 1,000 g. gave 42.7 g. of pyrite and galena, which yielded 0.0016 grain of gold and 0.0037 grain of silver.

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the peninsula. In that case, it would be allied rather to the dikes of the Upper Silurian in Victoria than to the newer volcanic rocks of its immediate neighborhood.

A prepared thin section of this rock was microscopically examined by a German mineralogist, who says of it:

"This rock is, without doubt, one of the older volcanic rocks. It consists of feldspar, mica, and hornblende, with a little quartz and magnetite. Mica is to a great extent absorbed, and magnetite has taken its place. The rock is difficult to classify, but would be best described as an elæolite-syenitic rock."

2. Samples 29 to 34 are from the Thames district. It was found difficult to get samples of the Thames andesites in which

the analysis of 5 g. would show no trace of sulphides—this being, as already explained, a requisite condition for the particular investigation in hand. A large number of samples had to be rejected on this account; but in Nos. 29 to 34 no trace of sulphides was found. . . .

3. Nine samples in Table I.: namely, Nos. 6, 11, 13, 17, 26, 36, 38, 46, and 47—contained sulphides. The results of further examination were as follows:

No. 6. Sample of 500 g. gave 53 g. of sulphides, mostly pyrrhotite and chalcopyrite, which contained 0.0053 grain of silver.

No. 11. Sample of 500 g. gave 18.56 g., chiefly pyrrhotite. No gold or silver.

No. 13. Sample of 1,000 g. gave 12.18 g. of pyrrhotite and arsenopyrite. No gold or silver.

No. 17. Sample of 1,000 g. gave 4.934 g. of pyrite, containing 0.037 grain of gold and 0.0041 grain of silver.

No. 26. Sample of 1,000 g. gave 28.92 g. of arsenopyrite and pyrrhotite, with a little galena, containing 0.0032 grain of gold and 0.0019 grain of silver.

No. 36. Sample of 1,000 g. gave 16.48 g. of chalcopyrite, with a small quantity of bournonite, carrying 0.407 grain of silver and no gold.

No. 38. Sample of 1,000 g. gave 16.03 g. of pyrite. No gold or silver.

No. 46. Sample of 1,000 g. gave 8.42 g. of pyrite. No gold or silver.

No. 47. Sample of 500 g. of pyrite and sphalerite, containing 0.0016 grain of gold and 0.0037 grain of silver.

Conclusions.—The results summarized in Table I. were greatly surprising to the writer. In view of the usually tedious character of the operation of isolating the various constituents of a rock, he would not have examined so large a number of samples had he not expected, at each new analysis, that he might succeed in discovering gold in some mineral other than a sulphide.

It is, perhaps, comparatively easy to conceive why, in a stratified area, gold may occur only in connection with sulphides; but that in such a rock as gneiss, granite, syenite, or diorite, it should form no part of the crystalline constituents, but, on the contrary, should occur only in the sulphides found in these rocks, seems more remarkable and significant.

Chapter VI.—The Vadose Region.

Professor Posepny[10] advances the sweeping proposition that the formation of ore-deposits could have taken place by descension and lateral secretion in the vadose region of circulation only, and must have been, in the deep region, the product of ascending currents. This distinction is, perhaps, too sharply drawn by him. It seems to the writer that the lateral-secretion theory can scarcely be put out of court by assuming a lateral secretion to be impossible below the ground-water level. Yet the marked difference everywhere observed in the contents of auriferous lodes above and below that level required that the rocks of the two zones should be distinguished, and separately analyzed in this investigation.

From an economic stand-point, this difference is expressed by the almost universal experience in the Australasian gold-fields, that the average yield of gold is much smaller below the water-level than near the surface. This statement, which will doubtless be controverted in some quarters, is based on the concurrent testimony of a large number of mine-managers and others, having long experience in the auriferous deposits of Australia and New Zealand. The almost unanimous evidence is in favor of the greater richness of vadose deposits. Several men of great experience have even given the opinion that, for ounces per ton above the ground-water level, only pennyweights per ton have been found below it.

This important economic question is naturally discussed in treatises on ore-deposits. Phillips,[11] for example, gives a number of reasons why the results in the vadose region may seem to be, while they are not really, higher than those of deep levels. Even after taking these considerations into account, however, the evidence of greater richness in the vadose region in Australia seems overwhelming.

In this connection, reference may be made to the exhaustive work of R. Brough Smyth,[12] and to a very interesting little work,[13] dealing with the yield of the auriferous deposits of Vic-

[10] *Trans.*, xxiii., 262 (1893).

[11] *A Treatise on Ore-Deposits*, pp. 60 to 62 (1884).

[12] *Gold-Fields of Victoria*, pp. 233 to 281 (1889).

[13] *The Gold-Fields of Victoria in* 1862, by a Special Reporter of the *Argus*, Melbourne (1863).

toria from 1851 to 1862. The reader of the latter book may suspect the anonymous author of overstating the facts; but a comparison of the average yields noted in it with those of mines now working in the same reefs, with the aid of the latest gold-saving appliances, can hardly fail to carry conviction, even to those who, permitting "the wish" to be "father to the thought," deny the impoverishment of auriferous lodes in depth.[14]

This greater richness of the vadose region might be explained in either of two ways.

1. If the auriferous contents of the lodes are derived from some deeper source, and have been deposited from warm ascending waters, the decrease of pressure on approaching what was, at the time of the lode-formation, the surface, might account for the precipitation of the precious metals in greater quantities near that surface.

2. If the reefs and their auriferous contents are due to the leaching action of solutions traversing the country-rock on each side of the fissures, such leaching action would naturally be far more intense near the surface, because the oxidizing action of the surface-water would naturally be much greater in the vadose region.

Either of these hypotheses might account for the greater richness of the vadose region. In the first case we might have in the present deposits of that region an example of the resolution and precipitation of gold which had been previously brought up from greater depths; while in the second case we might expect to trace a leaching action similar to that occurring in depth, only augmented by the effect of the oxidizing vadose waters.

The question is naturally suggested, whether natural reagents capable of dissolving gold[15] are to be found in the vicinity of auriferous lodes. And this inquiry suggests the further questions: Does gold exist in solution in mine-waters of either the vadose or the deep circulation? Does the gold of the vadose circulation, in any particular mine, contain a

[14] The gold-field of Bendigo is often cited as an instance to the contrary, good yields having been there obtained in some cases from great depths (2,000 to 2,800 ft.); but the reason for this is indicated in the remarks of E. J. Dunn, in his report on the *Bendigo Gold-Fields*, pp. 6 and 9.

[15] Gold is so easily precipitated from solution that an investigation as to possible precipitating-agents is scarcely necessary.

smaller percentage of silver than that of the deep circulation? Is any evidence of re-solution and re-precipitation to be obtained by analyzing samples of country-rock from the vadose region, corresponding in position with samples from the deep region of the same district?

Natural Solvents of Gold.

The chief solvents of gold at all likely to occur in the neighborhood of lodes are bromine, iodine, ferric chloride, ferric sulphate, and chlorine.

Bromine and Iodine.—The action of iodine as a solvent for gold in nature has been emphasized by some writers;[16] but, whatever may have taken place in the past, the present investigation seems to show that iodine is not at all abundant in auriferous rocks. The partial or complete analysis of 53 samples of mine-water from both the vadose and the deep circulation has detected no bromine, and only in one instance any trace of a soluble iodide. If, however, bromides and iodides do exist in the vadose region, the agents which liberate chlorine (considered below) would also liberate bromine and iodine.

Ferric Chloride and Ferric Sulphate.—Henry Wurtz[17] remarks that as early as 1859 he called attention to the solubility of gold in these salts; but he does not state the strength of the solvent solutions employed. The same is true of many other assertions of this reaction, encountered in technical literature.[18] It was therefore deemed necessary in the present investigation to test the solubility of gold in solutions of the above salts of various strengths, not greatly exceeding, however, the degree of concentration actually found in the most highly mineralized waters analyzed. Solutions of ferric chloride and ferric sulphate, containing from 1 to 20 g. per liter, were prepared, and finely divided (1) metallic gold and (2) auriferous sulphides were treated in these solutions, being freely exposed to the air at ordinary temperature for several months; but no gold was dis-

[16] For example, T. A. Rickard, On the Origin of the Gold-Bearing Quartz of the Bendigo Reefs, *Trans.*, xxii., 309 (1893).

[17] Gold Genesis, *Scientific American Supplement*, vol. xxxviii., No. 979, p. 15,644 (Oct. 6, 1894).

[18] It is highly desirable that in all such statements of solubility, the precise strength of the reagents should be given. Most of the accounts of the solution of gold, for instance, employ, at best, only the vague terms "strong," "dilute," etc.

solved, even by the strongest solutions. As the highest strength above named considerably exceeded that of the most highly mineralized mine-waters analyzed, no experiments were made with still stronger solutions of the ferric salts.

The negative result of these experiments is, of course, not conclusive proof that gold may not have been dissolved by these reagents in the vadose circulation in a longer time and under other conditions than those supplied.

Chlorine.—Possibly many reactions in nature, not easily reproduced in the laboratory, may liberate chlorine, even at ordinary temperatures. We know, however, that it is produced by the action of hydrochloric acid on the higher oxides of manganese, or by the action of sulphuric acid on the same oxides in the presence of chlorides.

The question whether agents for the re-solution of gold exist in the vadose region is thus practically narrowed to a search, in the waters and rocks of that region, for (1) free hydrochloric acid; (2) free sulphuric acid; (3) the higher oxides of manganese; and (4) ferric chloride and ferric sulphate.

It was desirable, at the outset, to determine the most dilute solution of hydrochloric acid which will, in the presence of the higher oxides of manganese, liberate sufficient chlorine to be detected by ordinary tests. Experiment showed that 1 part of hydrochloric acid of 1.16 sp. gr. in 2,500 of water would give a distinct chlorine reaction, while 1 part of the same acid in 1,250 of water produced chlorine enough to dissolve an amount of gold appreciable by delicate tests. As the proportion of pure HCl to water is in the first case only about 1 to 8,000, and in the second case 1 to 4,000, it is evident that extremely dilute acid will, in the presence of manganese oxides, dissolve gold.

Cause of Acidity in Mine-Waters.—The chief cause of acidity in mine-waters (see examples below) is without doubt the oxidation of pyrite, which yields ferric sulphate and sulphuric acid. The latter, acting on the chlorides, which are always present to greater or less extent in mine-waters, frees hydrochloric acid. The writer has never found a water containing free acid in which there was not also a large percentage of ferric salts.

The Occurrence of Oxides of Manganese in Mining-Districts.—

In some mining-districts (notably in Karangahake, in the Thames gold-field) the oxides of manganese often form a great part of the lode-filling. While this, however, is exceptional in Australia and New Zealand, the presence of the higher oxides of manganese in the ferric oxides of the vadose circulation is surprisingly general. Twenty analyses of such material from various localities showed in 17 cases manganese, representing from 0.012 to 43.59 per cent. (reckoned as Mn_3O_4). To one sample, containing only 0.38 per cent. of Mn_3O_4, dilute hydrochloric acid and precipitated gold were added, and gold was found to be dissolved.

If, therefore, the vadose mine-waters are found to contain free hydrochloric acid, it is evident that agents for the re-solution of gold in that zone are not lacking.

The Acidity of Vadose Mine-Waters.—An acid reaction with test-paper does not prove the presence of free acid. Every water examined which contained an appreciable quantity of ferric salts gave a distinct acid reaction, though in a number of cases examination proved the absence of free acid.

Seventeen samples of vadose waters were examined for free acid; care being taken to collect the water as it ran from the rock or vein, before any considerable exposure to oxidizing agencies other than the oxygen held in solution by the water itself.

In calculating the results from those samples which carried much free acid, if both sulphates and chlorides were present, and the amount of free acid exceeded the amount represented by the chlorine radical in the water, the whole of the chlorine radical was taken as combined with H to form free hydrochloric acid, and the remainder of the free acid found was reckoned as sulphuric acid. The results are shown in Table II. The amount of ferric chloride and sulphate can be approximately calculated from the proportion of iron present as ferric salts. Even after complete oxidation by exposure to the air, the total weight of ferric salts could never exceed 12 g. per liter. For this reason, in the experiments previously described (see p. 173), I did not use solutions of ferric salts containing more than 20 g. per liter.

Table II. shows the considerable increase in acidity caused by exposure to the air. It is noteworthy that all the samples

marked *, when taken from the mine, precipitated gold from solution, but that the same waters, after thorough oxidation, dissolved metallic gold when the higher oxides of manganese were added to them.

TABLE II.—*Examination of Mine-Waters of the Vadose Region for Free Acid and Ferric Salts.*

Sample.	Country-Rock.	Reaction to Test-Paper.	Free Acid in Grams per Liter before Exposure to Air.		Free Acid in Grams per Liter after Exposure to Air.		Total Weight of Iron in Grams per Liter.	Iron Present as Ferric Salts.	Iron Present as Ferrous Salts.
			HCl.	H_2SO_4.	HCl.	H_2SO_4.			
*a**	Propylite, highly pyritous.	Strongly acid.	0.446	7.901	0.446	8.650	3.198	2.431	0.767
*b**	Do.	Do.	0.287	Nil.	0.592	1.3842	2.471	0.946	1.525
*c**	Do.	Acid.	0.065	Nil.	0.208	Nil.	1.086	0.731	0.355
*d**	Do.	Strongly acid.	0.506	6.078	0.506	8.921	2.017	0.896	1.111
*e**	Do.	Acid.	0.079	Nil.	0.361	Nil.	0.968	0.834	0.134
*f**	Propylite and rhyolite.	Acid.	0.216	Nil.	0.465	0.380	0.758	0.210	0.548
*g**	Propylite, pyritous.	Acid.	0.409	1.063	0.605	1.582	1.903	1.127	0.776
h	Mica-schist.	Neutral.	Nil.	Nil.	Nil.	Nil.	0.095	0.027	0.068
i	Mica-schist.	Neutral.	Nil.	Nil.	Nil.	Nil.	0.872	0.305	0.567
j	Slate and sandstone.	Highly acid.	Nil.	Nil.	Nil.	Nil.	0.569	0.481	0.088
k	Mica-schist.	Do.	0.087	Nil.	0.105	Nil.	1.007	0.783	0.224
l	Mica-schist.	Strongly acid.	0.658	Nil.	0.816	Nil.	1.569	1.406	0.163
m	Mica-schist.	Slightly acid.	0.064	Nil.	Nil.	Nil.	0.987	0.639	0.348
n	Mica-schist.	Neutral.	Nil.	Nil.	Nil.	Nil.	0.640	0.379	0.261
o	Mica-schist.	Acid.	Nil.	Nil.	0.406	Nil.	1.206	0.217	0.989
p	Slate and sandstone.	Neutral.	Nil.	Nil.	Nil.	Nil.	0.489	0.426	0.063
q	Do.	Neutral.	Nil.	Nil.	Nil.	Nil.	0.602	0.578	0.024

a. From the Whau mine, Thames, N. Z. Contained a large quantity of iron in solution. Color, wine-red. Sp. gr., 1.021.

b. From Maria reef, Karangahake, Thames, N. Z. Deposited a large quantity of ferric hydroxide on standing.

c. From Woodstock reef, Thames, N. Z. Behaved on standing like sample *b*.

d. From the Alburnia mine, Thames, N. Z. In appearance like sample *a*. Sp. gr., 1.019.

e. From the Grace Darling mine, Thames, N. Z. Nearly clear; slight deposit of ferric hydroxide on standing.

f. From the Martha mine, Waihi, Thames, N. Z. Appearance and behavior on standing like sample *e*.

g. From the Crown mine, Karangahake, Thames, N. Z. Like samples *e* and *f*.

h. From the Tipperary mine, Macetown, Otago. Clear.

i. From the Premier mine, Macetown, Otago. Clear.

j. From the Long Tunnel, Walhalla, Victoria. Clear.

k. From the Bonanza mine, Nenthorn, Otago. Clear.

l. From a quartz reef near Roxburgh, Otago. Reddish; deposited a good quantity of ferric hydroxide on standing.

m. From the Bella reef, Waipori, Otago. Clear.

n. From the Gabriel's Gully reef, Lawrence, Otago. Clear.

o. From the Game Hen reef, Hindon, Otago. Clear.

p. From the reef on Sovereign hill, Ballarat, Victoria. Clear.

q. From the reef on Big hill, Bendigo, Victoria. Clear.

The results shown in Table II. point to the following conclusions:

1. In districts like the Thames, N. Z., where the country-rock is highly charged with sulphides, the vadose water may often contain free hydrochloric acid sufficient (when the higher oxides of manganese are present) to re-dissolve gold. Though the Thames samples were incapable of holding ordinary salts of gold in solution, they acted as solvents of gold when they were thoroughly oxidized and manganese oxides were present.

2. The great majority of the mine-waters analyzed contained no free acid which could liberate chlorine by acting on the oxides of manganese that are abundant near quartz reefs.

3. The higher salts of iron are not present in any samples of water analyzed by me, in sufficient quantity to dissolve gold at ordinary temperatures. (Stronger solutions of these salts failed to dissolve gold.) It may be added, that in every case in which much iron was present, free acids were also found; so that in any solution of gold that might be effected, the more powerful solvent, chlorine, might also be acting.

Notwithstanding these conclusions, I must point out that the re-solution of gold has probably gone on, and is still going on, in the vadose region, even where the vadose waters contain neither free hydrochloric acid nor notable quantities of ferric salts. The analyses of samples from the vadose regions of Walhalla and Ballarat (see Tables III. and IV., and Figs. 1 and 2 [Tables XX. and XXI. and Diagrams 8 and 9 of original paper]), the vadose waters of which contained no free acid and were very poor in dissolved minerals, show that such re-solution has probably been considerable, though we find no agencies now existing which would account for it.

Does Gold Exist in Mine-Waters of Either or Both Circulations?

Prof. A. Liversidge[19] has pointed out that the search for gold in meteoric and mine-waters has not proved its presence in solution. It has been detected, but it may have been in mechanical suspension. So far as I know, Messrs. Norman Taylor and Cosmo Newbery, of the Victorian Geological Survey, are the only persons who have experimentally investigated this subject

[19] On the Origin of Gold Nuggets, *Proceedings of the Royal Society of New South Wales*, vol. xxvii., p. 303 (1893).

in these colonies. Mr. Newbery, who made the most experiments, said before the Victorian Royal Commission on Gold-Mining [20] that whenever he got gold, he got also angular fragments of quartz, which could find its way wherever gold could find its way, and both might have been conveyed mechanically.

The evidence for the existence of gold in mine-waters rests, so far as I am aware, on the discovery of gold: (1) in boiler-scale from boilers fed with mine-water; and (2) in wood taken from old mine-workings, where it has been covered for some time with mine-water—the latter being assumed to have carried dissolved gold into the timber, to be precipitated by the organic matter of the wood. But the finding of gold under such circumstances does not prove that it was in solution in mine-waters at deep levels. In the first case, the gold may have been carried into the boiler in suspension, along with the silt which all mine-waters contain. In the second case, even though gold may have been dissolved in the water surrounding the old timbers, it may have been brought into such solution by the action of air in the mine-workings, oxidizing sulphides of the rock to sulphates and setting free sulphuric acid, which, in turn, acting on the chlorides always present in mine-waters, would liberate hydrochloric acid. This acid, acting on oxides of manganese, would free chlorine, which would dissolve gold. This statement applies particularly to all mines the waters of which contain considerable iron. Every sample of chalybeate mine-water analyzed by me acted as a precipitant of gold when taken fresh from the workings, but as a solvent of gold at ordinary temperatures, in the presence of the oxides of manganese, when it had been exposed to the air for a week or two.

Mr. Newbery, however, distinctly said, in his testimony already cited, that he found angular quartz which had been soaked up into the timber examined, and that the gold might have been mechanically introduced in the same way.

With regard to the suspension of gold in mine-waters, the following evidence, obtained by me last year, may be of interest.

In the Long Tunnel G. M. Co.'s mine at Walhalla, Gippsland, Victoria, one of the most productive mines in Australia,[21]

[20] *Report of the Commission*, p. 68 (1893).

[21] Ramsay Thompson, the general manager, to whom I am indebted for much kind assistance, informed me that up to December, 1894, this mine had produced over 22 tons of gold, and had paid £1,200,000 in dividends.

the water pumped from various depths, down to about 2,300 ft. below the surface, is run into two large settling-tanks, before using. At the time of my visit one of these tanks contained a large quantity of fine silt, which had been suspended in the mine-water. I analyzed three samples of about 2 lb. each, first panning off the lighter part, and then assaying the residue. The first sample gave 0.0063 grain of gold; the second, no trace; and the third, 0.0175 grain.

These results show that assays of boiler-scale do not necessarily prove that gold was dissolved in the water depositing it; and, also, that in all analyses even of samples from the vadose circulation, to test the presence of dissolved gold, care must be taken to free the water beforehand from every trace of suspended matter.

I have tested many old mine-timbers for gold. In every case the outside wood was chipped off to the depth of about 0.5 in.; and, when cracks appeared in the timber, about 0.5 in. on each side of the crack was also chipped off. These parts were burned, and analyzed separately from the inner portions. The results of several such analyses are shown in the table on p. 180.

Search for Gold in Mine-Waters.—It was soon found useless to examine mine-waters which contained much iron, and in which the ferrous salts had not been oxidized to ferric salts by exposure to the atmosphere. The analyses were consequently restricted, for the vadose region, to waters containing a very small percentage of iron-salts, and chalybeate waters which had been thoroughly oxidized (the latter being apparently exceptional, even in that region), and, for the deep circulation, to waters containing so little iron that they do not act as precipitants of gold.

This chapter treats of mine-waters under the conditions of temperature and pressure now encountered. What might be effected by these waters under other conditions does not concern us at this stage.

If gold be present in mine-waters at all, it is likely to be in very minute proportions. Hence large quantities of water must be operated upon. The method of evaporation for the assay of the residue was too tedious, especially in view of the limited time at my disposal in each locality. I therefore availed myself of the well-known action of sulphides and organic matter in precipitating gold from solution.

Analyses of Old Mine-Timbers.

Sample.	Description and Locality.	Part Analyzed.	Gold Found.
I.	Prop from the Tipperary Gold Mining Co., Macetown, Otago, much decomposed. The part analyzed had been under water for many years	Outside of the prop.	None.
II.	Do.	Inside of prop.	None.
III.	Prop from an old tunnel in an alluvial terrace, near Skipper's Point, Otago. The part analyzed had been under water for probably 20 years.	Outside of prop.	None.
IV.	Do.	Inside of prop.	None.
V.	A prop from the Premier mine, Macetown, Otago. Water had been running over it for 2 years at least.	Outside of prop.	0.0038 grain.
VI.	Rotten wood from the lower part of a rejected prop from the Long Tunnel Gold Mining Co., Walhalla. From a part of the mine where a richly auriferous reef had been worked.	Outside of prop.	0 0097 grain.
VII.	Do.	Inside of prop.	None.
VIII.	Decayed portion of lath brought up from the deep workings of the Northern Star Gold Mining Co., Ballarat. Had evidently been saturated with water for many years.	No portion was sound; all was burned and analyzed.	None.
IX.	Portion of sleeper used in a tramway, Northern Star Gold Mining Co., much decayed. A large quantity of water had been running over it for at least a year.	Do.	0.0129 grain.

A filter was constructed, consisting of a tinned-iron cylinder, about 3 in. in diameter and 6 in. long, terminating below in a funnel, inside of which was placed a filter of glass-wool, and above this the reducing-agents (animal charcoal, artificial iron and lead sulphides, roughly powdered). The upper part was connected by a rubber tube with the tap supplying the water to be tested.

The following preliminary test proved the efficiency of this filter: A solution in 400 gal. of water (from the Dunedin water-mains) of 28 lb. of common salt, 8 oz. of magnesium sulphate, 8 oz. of ferric chloride, and 0.1 grain of gold in the form of auric chloride, was allowed to trickle slowly through the filter, the operation taking about 48 hr. The mixture of sulphides and

charcoal was then removed, roasted, and assayed, when 0.0926 grain of gold was recovered, showing that practically all the gold had been precipitated.

In examining mine-waters, the water was first collected in an iron tank, and powdered alum was added to it, completely precipitating all suspended matter. After standing some hours, it was tapped from 2 or 3 in. above the bottom of the tank, and filtered as described.

Four samples were thus treated; but in no case was gold found.

The first sample (about 500 gal.) was water from the high-level tunnel of the Tipperary G. M. Co., which had percolated down from the surface through the lode-fissure for from 200 to 500 ft., and flowed in a large stream from the tunnel-mouth. This practically represented the vadose circulation only.

The second sample (about 500 gal.) was from the pump-discharge of the New Chum Railway Co., Bendigo, Victoria, and represented the whole drainage of the mine from the surface to a depth of 2,850 feet.

The third sample (about 700 gal.) was from the Long Tunnel G. M. Co.'s mine, Walhalla, Victoria, near a very rich lode, and represented the whole drainage between the adit (700 ft. below the summit of the hill) and a level about 2,300 ft. below the surface, or over 1,500 ft. below the adit.

The fourth sample (about 500 gal.), from a deep tunnel of the Premier mine, Advance Peak, Otago, driven on a lode which had proved richly auriferous in places, represented the whole drainage from the surface to probably 2,000 ft. below it.

The negative results of these tests are the more surprising to me, since other examinations, hereinafter described, afforded strong evidence that solution and re-precipitation of gold have taken place in the vadose region.

It is, of course, possible that gold may have existed in these samples in some form from which it was not precipitated by the reagents used. This is suggested, indeed, by my experience (see Chapter VII.) in attempting to precipitate gold from sea-water. The question can only be decided by the evaporation of samples (first freed from suspended matter) in larger amount and number than mine, and the assay of the residues. I venture to recommend such an inquiry to those who live in the vicinity of rich mines and have time for the work.

Does the Gold of the Vadose Region Contain Generally Less Silver than That of the Deep Circulation in the Same District?

Several investigations have seemed to prove that, on the average, the gold of the alluvial deposits in Australia and elsewhere is appreciably finer in quality than the vein-gold. The matter has been discussed chiefly in connection with the origin of nuggets;[22] but, so far as I know, no comparison as to fineness has been made between the vadose and the deep vein-gold.

The observed difference between placer- and vein-gold may be held to show, either that the oxidized mineral-bearing waters running in the ancient drift-deposits dissolved out part of the silver with which the gold was alloyed, or else that these waters dissolved both gold and silver, the gold being again precipitated, alloyed with less silver than before. Similar reasoning might be applied to an observed difference between the vadose and the deep zone, in the quality of vein-gold. I have therefore made comparative assays of this character in a number of cases.

The fineness of the gold may vary considerably even in the same level, and within a few feet. This is true even in such districts as Bendigo, Ballarat, and Otago, where the percentage of silver is comparatively low, while in districts like the Thames, N. Z., the variation observed is sometimes extraordinary. On the whole, however, the average quality of the gold won in districts of the former class varies little.

Five localities were chosen (chiefly by reason of facilities for obtaining specimens from near the surface), namely, (1) the Nenthorn gold-field, in mica-schist, in eastern Otago; (2) the Tipperary and Premier mines, in mica-schist, Macetown, central Otago; (3) the Dart river, in northern Gippsland, representing the Upper Silurian of Victoria; (4) the Bendigo field,[23] representing the Lower Silurian; and (5) the Thames district of the North Island, in altered Lower Tertiary andesite.

In a few instances the analyses were made of gold picked out of the reef; but the majority were assays of vein-stone.

[22] Professor Liversidge, in the paper already cited, gives a convenient summary of the literature of this subject.

[23] Surface-samples are hard to get in Bendigo. Nearly all the companies are mining in the deep region, and have long ago exhausted the pay-quartz above. I took many samples from outcrops of reefs, but found in the majority little or no gold. The results given below are those in which a prill of appreciable size was obtained by assaying 1,000 grains of vein-stone.

The percentage of silver was in each case obtained by difference, and represents the loss per cent. of the prill after quartation. The results were as shown in the table on p. 184.

These analyses of 76 samples go, on the whole, to prove that the average fineness of the gold in the vadose region is appreciably greater than in the deep circulation in the same district, and also that the vadose gold is considerably more regular in quality.

It seems to be indicated that considerable solvent action must have been exercised by water percolating through the rocks of the vadose region, as the denudation of the surface has gradually lowered the water-level, converting the deep circulation of former times into the vadose of to-day.

Analyses of Vadose Country-Rock, etc., at Different Distances from Auriferous Lodes.

At the beginning of this chapter I have pointed out the importance of separate rock-assays in the vadose region. It was relatively difficult to obtain good samples (other than surface-samples) of this class, because most of the mines are now deep, and the former long cross-cuts run on upper levels into the country-rock are abandoned and closed. The samples therefore comprise chiefly oxidized rock from pretty near the lodes, and 10 to 100 ft. below the surface, and surface-samples taken at all distances from the lodes. Particular interest attaches to samples of (1) oxide of iron and manganese deposited along bedding-planes or fractures; (2) solid rock as little altered as possible by the action of percolating water; and (3) secondary[24] sulphides, abundant in the vadose region of many mines.

The remarks covering the methods of concentration and assay pursued with samples from the deep levels, apply here also.

[24] In calling these vadose sulphides "secondary," I mean that they have probably been formed through the oxidization of the sulphides of the deep circulation by surface-water, followed by a reduction of the sulphates and re-precipitation of the sulphides by organic matter. I do not mean to say positively that the sulphides of the deep zone are not, as many observers believe, also secondary in this sense, that is, due to the reducing action of carbonaceous matter upon soluble sulphates. This is Sandberger's view (*Untersuchung*, etc., vol. i., p. 21). Yet so far as my experience of the deep sulphides goes, it certainly favors the theory of their formation by the action on the silicates of metals of hydrogen sulphide, dissolved in ascending water.

Relative Fineness of Vadose and Deep Vein-Gold.

A. Surface-Samples from Nenthorn Gold-Field, Otago, N. Z.

No.	Percentage of Gold.	Percentage of Silver.
1	91.85	7.15
2	89.27	10.73
3	90.43	9.67
4	89.19	10.81
5	92.01	7.99
6	89.38	10.62
7	91.46	8.54
8	90.79	9.21
9	90.07	8.53
10	92.00	8.00

Average fineness of 10 samples, 90.645 per cent. Range of fineness, 89.19 to 92.01 = 2.827 per cent.

B. From Deeper Levels of Nenthorn District (the Bulk of the Gold was Held by Pyrite).

No.	Percentage of Gold.	Percentage of Silver.
1	89.86	10.14
2	91.43	8.57
3	87.17	12.83
4	90.45	9.55
5	89.07	10.93
6	92.01	7.99
7	90.17	9.83
8	88.75	11.25
9	91.03	8.97
10	90.30	9.70

Average fineness of 10 samples, 90.024 per cent. Range of fineness, 87.17 to 92.01 = 4.84 per cent.

C. Surface-Samples from Tipperary Premier, and Sunrise Gold Mining Companies. All near Macetown, Central Otago, N. Z.

No.	Percentage of Gold.	Percentage of Silver.
1	96.12	3.88
2	93.37	6.63
3	94.19	5.81
4	92.87	7.53
5	95.00	5.00
6	94.58	5.42
7	93.23	6.77
8	95.84	4.16
9	95.93	4.07
10	94.89	5.11

Average fineness of 10 samples, 94.602 per cent. Range of fineness, 92.87 to 96.12 = 3.25 per cent.

D From Deep Levels (1,000 to 1,500 Ft. Below Surface) in Tipperary and Premier Mines, Macetown.

No.	Percentage of Gold.	Percentage of Silver.
1	95.39	4.61
2	94.48	5.52
3	91.87	8.13
4	96.29	3.71
5	93.06	6.94
6	94.31	5.69
7	93.80	6.20
8	94.73	4.27
9	93.90	6.10
10	94.10	5.90

Average fineness of 10 samples, 94.293 per cent. Range of fineness, 91.87 to 96.29 = 4.42 per cent.

NOTE.—A sample taken from a bar of 194 oz. from deep levels of Premier Gold Mining Co. contained 94.45 per cent.

E. Surface-Specimens from Richly Auriferous Lode in the Vicinity of the Dart River, North Gippsland, Victoria.

No.	Percentage of Gold.	Percentage of Silver.
1	91.87	8.13
2	94.96	5.04
3	93.08	6.92
4	92.00	8.00
5	92.63	7.37
6	94.73	5.27
7	93.45	6.55
8	95.01	4.99
9	94.91	5.09
10	92.84	7.18

Average fineness of 10 samples, 93.548 per cent. Range of fineness, 91.87 to 95.01 = 4.14 per cent.

F. Unoxidized Specimens from the Same Reef, Dart River, North Gippsland, Victoria.

No.	Percentage of Gold.	Percentage of Silver.
1	91.50	8.50
2	90.43	9.57
3	87.69	12.31
4 [a]	96.28	3.72
5	91.17	8.83
6 [b]	84.64	15.36
7	88.93	11.07
8	95.03	4.97
9	90.37	9.63
10	90.80	9.20

Average fineness of 10 samples, 90.984 per cent. Range of fineness, 84.64 to 96.28 = 12.36 per cent.

[a] Sample assayed consisted of arsenopyrite and pyrite.

[b] Sample assayed composed chiefly of galena.

Relative Fineness of Vadose and Deep Vein-Gold.—Continued.

G. Surface-Samples from Bendigo Gold-Field, Victoria.

No.	Percentage of Gold.	Percentage of Silver.
1	94.76	5.24
2	95.03	4.97
3	94.05	5.95
4	94.27	5.73
5	94.10	5.90
6	95.00	5.00

Average fineness of 6 samples, 94.535 per cent. Range of fineness, 94.05 to 95.03 = 0.98 per cent.

H. Samples from Deep Levels (1,200 to 3,000 Ft.) of Bendigo Gold-Field.

No.	Percentage of Gold.	Percentage of Silver.
1	93.08	6.92
2	95.04	4.96
3	94.00	6.00
4	91.27	8.73
5	91.30	5.70
6	94.19	5.81
7	93.96	6.04
8	92.95	7.05
9	92.37	7.63
10	94.70	5.30

Average fineness of 10 samples, 93.586 per cent. Range of fineness, 92.37 to 95.04 = 2.64 per cent.

I. Samples from Vadose Region of Various Parts of Thames District, N. Island, N. Z.

No.	Percentage of Gold.	Percentage of Silver.
1	63.72	36.28
2	79.34	20.66
3	52.90	47.10
4	57.39	42.61
5	67.01	32.99
6	59.98	40.02
7	65.55	34.45
8	73.07	36.93
9	60.08	39.92
10	51.19	48.81

Average fineness of 10 samples, 60.023 per cent. Range of fineness, 51.19 to 79.34 = 28.15 per cent.

K. Samples from Deep Circulation of the Thames District.

No.	Percentage of Gold.	Percentage of Silver.
1	63.76	56.24
2	71.14	28.86
3	59.93	40.07
4	53.01	46.99
5	64.25	35.75
6	43.17	56.83
7	66.98	33.02
8	51.30	48.70
9	69.04	30.96
10	48.75	51.25

Average fineness of 10 samples, 59.133 per cent. Range of fineness, 43.17 to 71.14 = 27.97 per cent.

[In the majority of cases the samples taken weighed 7 or 8 lb.; the samples tested, 4.48 lb.; and the assays were made from concentrates of the latter, but sometimes 4.48 lb. was the actual sample for assay; in which case the total quantity was pulverized to pass a No. 60 sieve, and divided into 12 parts of about 2,500 grains each, and to each part 3,000 grains of purified litharge, 2,000 grains of carbonate of soda, and 1,000 to 1,500 grains of borax were added for the assay, with sufficient argol to reduce about 400 grains of lead.]

But concentration of an oxidized rock is much more difficult, because oxidation destroys the heavy sulphides, and also liberates very finely divided gold, which there is danger of losing. Hence my results with vadose country-rock are not quantitatively correct. To minimize the probable error, the samples were not concentrated nearly as far as those from deep levels had been.

solved, even by the strongest solutions. As the highest strength above named considerably exceeded that of the most highly mineralized mine-waters analyzed, no experiments were made with still stronger solutions of the ferric salts.

The negative result of these experiments is, of course, not conclusive proof that gold may not have been dissolved by these reagents in the vadose circulation in a longer time and under other conditions than those supplied.

Chlorine.—Possibly many reactions in nature, not easily reproduced in the laboratory, may liberate chlorine, even at ordinary temperatures. We know, however, that it is produced by the action of hydrochloric acid on the higher oxides of manganese, or by the action of sulphuric acid on the same oxides in the presence of chlorides.

The question whether agents for the re-solution of gold exist in the vadose region is thus practically narrowed to a search, in the waters and rocks of that region, for (1) free hydrochloric acid; (2) free sulphuric acid; (3) the higher oxides of manganese; and (4) ferric chloride and ferric sulphate.

It was desirable, at the outset, to determine the most dilute solution of hydrochloric acid which will, in the presence of the higher oxides of manganese, liberate sufficient chlorine to be detected by ordinary tests. Experiment showed that 1 part of hydrochloric acid of 1.16 sp. gr. in 2,500 of water would give a distinct chlorine reaction, while 1 part of the same acid in 1,250 of water produced chlorine enough to dissolve an amount of gold appreciable by delicate tests. As the proportion of pure HCl to water is in the first case only about 1 to 8,000, and in the second case 1 to 4,000, it is evident that extremely dilute acid will, in the presence of manganese oxides, dissolve gold.

Cause of Acidity in Mine-Waters.—The chief cause of acidity in mine-waters (see examples below) is without doubt the oxidation of pyrite, which yields ferric sulphate and sulphuric acid. The latter, acting on the chlorides, which are always present to greater or less extent in mine-waters, frees hydrochloric acid. The writer has never found a water containing free acid in which there was not also a large percentage of ferric salts.

The Occurrence of Oxides of Manganese in Mining-Districts.—

In some mining-districts (notably in Karangahake, in the Thames gold-field) the oxides of manganese often form a great part of the lode-filling. While this, however, is exceptional in Australia and New Zealand, the presence of the higher oxides of manganese in the ferric oxides of the vadose circulation is surprisingly general. Twenty analyses of such material from various localities showed in 17 cases manganese, representing from 0.012 to 43.59 per cent. (reckoned as Mn_3O_4). To one sample, containing only 0.38 per cent. of Mn_3O_4, dilute hydrochloric acid and precipitated gold were added, and gold was found to be dissolved.

If, therefore, the vadose mine-waters are found to contain free hydrochloric acid, it is evident that agents for the re-solution of gold in that zone are not lacking.

The Acidity of Vadose Mine-Waters.—An acid reaction with test-paper does not prove the presence of free acid. Every water examined which contained an appreciable quantity of ferric salts gave a distinct acid reaction, though in a number of cases examination proved the absence of free acid.

Seventeen samples of vadose waters were examined for free acid; care being taken to collect the water as it ran from the rock or vein, before any considerable exposure to oxidizing agencies other than the oxygen held in solution by the water itself.

In calculating the results from those samples which carried much free acid, if both sulphates and chlorides were present, and the amount of free acid exceeded the amount represented by the chlorine radical in the water, the whole of the chlorine radical was taken as combined with H to form free hydrochloric acid, and the remainder of the free acid found was reckoned as sulphuric acid. The results are shown in Table II. The amount of ferric chloride and sulphate can be approximately calculated from the proportion of iron present as ferric salts. Even after complete oxidation by exposure to the air, the total weight of ferric salts could never exceed 12 g. per liter. For this reason, in the experiments previously described (see p. 173), I did not use solutions of ferric salts containing more than 20 g. per liter.

Table II. shows the considerable increase in acidity caused by exposure to the air. It is noteworthy that all the samples

marked *, when taken from the mine, precipitated gold from solution, but that the same waters, after thorough oxidation, dissolved metallic gold when the higher oxides of manganese were added to them.

TABLE II.—*Examination of Mine-Waters of the Vadose Region for Free Acid and Ferric Salts.*

Sample.	Country-Rock.	Reaction to Test-Paper.	Free Acid in Grams per Liter before Exposure to Air.		Free Acid in Grams per Liter after Exposure to Air.		Total Weight of Iron in Grams per Liter.	Iron Present as Ferric Salts.	Iron Present as Ferrous Salts.
			HCl.	H_2SO_4.	HCl.	H_2SO_4.			
*a**	Propylite, highly pyritous.	Strongly acid.	0.446	7.901	0.446	8.650	3.198	2.431	0.767
*b**	Do	Do.	0.287	Nil.	0.592	1.3842	2.471	0.946	1.525
*c**	Do	Acid.	0.065	Nil.	0.208	Nil.	1.086	0.731	0.355
*d**	Do	Strongly acid.	0.506	6.078	0.506	8.921	2.017	0.896	1.111
*e**	Do	Acid.	0.079	Nil.	0.361	Nil.	0.968	0.834	0.134
*f**	Propylite and rhyolite.	Acid.	0.216	Nil.	0.465	0.380	0.758	0.210	0.548
*g**	Propylite, pyritous.	Acid.	0.409	1.063	0.605	1.582	1.903	1.127	0.776
h	Mica-schist.	Neutral.	Nil.	Nil.	Nil.	Nil.	0.095	0.027	0.068
i	Mica-schist.	Neutral.	Nil.	Nil.	Nil.	Nil.	0.872	0.305	0.567
j	Slate and sandstone.	Highly acid.	Nil.	Nil.	Nil.	Nil.	0.569	0.481	0.088
k	Mica-schist.	Do.	0.087	Nil.	0.105	Nil.	1.007	0.783	0.224
l	Mica-schist.	Strongly acid.	0.658	Nil.	0.816	Nil.	1.569	1.406	0.163
m	Mica-schist.	Slightly acid.	0.064	Nil.	Nil.	Nil.	0.987	0.639	0.348
n	Mica-schist.	Neutral.	Nil.	Nil.	Nil.	Nil.	0.640	0.379	0.261
o	Mica-schist.	Acid.	Nil.	Nil.	0.406	Nil.	1.206	0.217	0.989
p	Slate and sandstone.	Neutral.	Nil.	Nil.	Nil.	Nil.	0.489	0.426	0.063
q	Do	Neutral.	Nil.	Nil.	Nil.	Nil.	0.602	0.578	0.024

a. From the Whau mine, Thames, N. Z. Contained a large quantity of iron in solution. Color, wine-red. Sp. gr., 1.021.

b. From Maria reef, Karangahake, Thames, N. Z. Deposited a large quantity of ferric hydroxide on standing.

c. From Woodstock reef, Thames, N. Z. Behaved on standing like sample *b*.

d. From the Alburnia mine, Thames, N. Z. In appearance like sample *a*. Sp. gr., 1.019.

e. From the Grace Darling mine, Thames, N. Z. Nearly clear; slight deposit of ferric hydroxide on standing.

f. From the Martha mine, Waihi, Thames, N. Z. Appearance and behavior on standing like sample *e*.

g. From the Crown mine, Karangahake, Thames, N. Z. Like samples *e* and *f*.

h. From the Tipperary mine, Macetown, Otago. Clear.

i. From the Premier mine, Macetown, Otago. Clear.

j. From the Long Tunnel, Walhalla, Victoria. Clear.

k. From the Bonanza mine, Nenthorn, Otago. Clear.

l. From a quartz reef near Roxburgh, Otago. Reddish; deposited a good quantity of ferric hydroxide on standing.

m. From the Bella reef, Waipori, Otago. Clear.

n. From the Gabriel's Gully reef, Lawrence, Otago. Clear.

o. From the Game Hen reef, Hindon, Otago. Clear.

p. From the reef on Sovereign hill, Ballarat, Victoria. Clear.

q. From the reef on Big hill, Bendigo, Victoria. Clear.

The results shown in Table II. point to the following conclusions:

1. In districts like the Thames, N. Z., where the country-rock is highly charged with sulphides, the vadose water may often contain free hydrochloric acid sufficient (when the higher oxides of manganese are present) to re-dissolve gold. Though the Thames samples were incapable of holding ordinary salts of gold in solution, they acted as solvents of gold when they were thoroughly oxidized and manganese oxides were present.

2. The great majority of the mine-waters analyzed contained no free acid which could liberate chlorine by acting on the oxides of manganese that are abundant near quartz reefs.

3. The higher salts of iron are not present in any samples of water analyzed by me, in sufficient quantity to dissolve gold at ordinary temperatures. (Stronger solutions of these salts failed to dissolve gold.) It may be added, that in every case in which much iron was present, free acids were also found; so that in any solution of gold that might be effected, the more powerful solvent, chlorine, might also be acting.

Notwithstanding these conclusions, I must point out that the re-solution of gold has probably gone on, and is still going on, in the vadose region, even where the vadose waters contain neither free hydrochloric acid nor notable quantities of ferric salts. The analyses of samples from the vadose regions of Walhalla and Ballarat (see Tables III. and IV., and Figs. 1 and 2 [Tables XX. and XXI. and Diagrams 8 and 9 of original paper]), the vadose waters of which contained no free acid and were very poor in dissolved minerals, show that such re-solution has probably been considerable, though we find no agencies now existing which would account for it.

Does Gold Exist in Mine-Waters of Either or Both Circulations?

Prof. A. Liversidge[19] has pointed out that the search for gold in meteoric and mine-waters has not proved its presence in solution. It has been detected, but it may have been in mechanical suspension. So far as I know, Messrs. Norman Taylor and Cosmo Newbery, of the Victorian Geological Survey, are the only persons who have experimentally investigated this subject

[19] On the Origin of Gold Nuggets, *Proceedings of the Royal Society of New South Wales*, vol. xxvii., p. 303 (1893).

in these colonies. Mr. Newbery, who made the most experiments, said before the Victorian Royal Commission on Gold-Mining [20] that whenever he got gold, he got also angular fragments of quartz, which could find its way wherever gold could find its way, and both might have been conveyed mechanically.

The evidence for the existence of gold in mine-waters rests, so far as I am aware, on the discovery of gold: (1) in boiler-scale from boilers fed with mine-water; and (2) in wood taken from old mine-workings, where it has been covered for some time with mine-water—the latter being assumed to have carried dissolved gold into the timber, to be precipitated by the organic matter of the wood. But the finding of gold under such circumstances does not prove that it was in solution in mine-waters at deep levels. In the first case, the gold may have been carried into the boiler in suspension, along with the silt which all mine-waters contain. In the second case, even though gold may have been dissolved in the water surrounding the old timbers, it may have been brought into such solution by the action of air in the mine-workings, oxidizing sulphides of the rock to sulphates and setting free sulphuric acid, which, in turn, acting on the chlorides always present in mine-waters, would liberate hydrochloric acid. This acid, acting on oxides of manganese, would free chlorine, which would dissolve gold. This statement applies particularly to all mines the waters of which contain considerable iron. Every sample of chalybeate mine-water analyzed by me acted as a precipitant of gold when taken fresh from the workings, but as a solvent of gold at ordinary temperatures, in the presence of the oxides of manganese, when it had been exposed to the air for a week or two.

Mr. Newbery, however, distinctly said, in his testimony already cited, that he found angular quartz which had been soaked up into the timber examined, and that the gold might have been mechanically introduced in the same way.

With regard to the suspension of gold in mine-waters, the following evidence, obtained by me last year, may be of interest.

In the Long Tunnel G. M. Co.'s mine at Walhalla, Gippsland, Victoria, one of the most productive mines in Australia,[21]

[20] *Report of the Commission*, p. 68 (1893).

[21] Ramsay Thompson, the general manager, to whom I am indebted for much kind assistance, informed me that up to December, 1894, this mine had produced over 22 tons of gold, and had paid £1,200,000 in dividends.

the water pumped from various depths, down to about 2,300 ft. below the surface, is run into two large settling-tanks, before using. At the time of my visit one of these tanks contained a large quantity of fine silt, which had been suspended in the mine-water. I analyzed three samples of about 2 lb. each, first panning off the lighter part, and then assaying the residue. The first sample gave 0.0063 grain of gold; the second, no trace; and the third, 0.0175 grain.

These results show that assays of boiler-scale do not necessarily prove that gold was dissolved in the water depositing it; and, also, that in all analyses even of samples from the vadose circulation, to test the presence of dissolved gold, care must be taken to free the water beforehand from every trace of suspended matter.

I have tested many old mine-timbers for gold. In every case the outside wood was chipped off to the depth of about 0.5 in.; and, when cracks appeared in the timber, about 0.5 in. on each side of the crack was also chipped off. These parts were burned, and analyzed separately from the inner portions. The results of several such analyses are shown in the table on p. 180.

Search for Gold in Mine-Waters.—It was soon found useless to examine mine-waters which contained much iron, and in which the ferrous salts had not been oxidized to ferric salts by exposure to the atmosphere. The analyses were consequently restricted, for the vadose region, to waters containing a very small percentage of iron-salts, and chalybeate waters which had been thoroughly oxidized (the latter being apparently exceptional, even in that region), and, for the deep circulation, to waters containing so little iron that they do not act as precipitants of gold.

This chapter treats of mine-waters under the conditions of temperature and pressure now encountered. What might be effected by these waters under other conditions does not concern us at this stage.

If gold be present in mine-waters at all, it is likely to be in very minute proportions. Hence large quantities of water must be operated upon. The method of evaporation for the assay of the residue was too tedious, especially in view of the limited time at my disposal in each locality. I therefore availed myself of the well-known action of sulphides and organic matter in precipitating gold from solution.

Analyses of Old Mine-Timbers.

Sample.	Description and Locality.	Part Analyzed.	Gold Found.
I.	Prop from the Tipperary Gold Mining Co., Macetown, Otago, much decomposed. The part analyzed had been under water for many years	Outside of the prop.	None.
II.	Do.	Inside of prop.	None.
III.	Prop from an old tunnel in an alluvial terrace, near Skipper's Point, Otago. The part analyzed had been under water for probably 20 years.	Outside of prop.	None.
IV.	Do.	Inside of prop.	None.
V.	A prop from the Premier mine, Macetown, Otago. Water had been running over it for 2 years at least.	Outside of prop.	0.0038 grain.
VI.	Rotten wood from the lower part of a rejected prop from the Long Tunnel Gold Mining Co., Walhalla. From a part of the mine where a richly auriferous reef had been worked.	Outside of prop.	0.0097 grain.
VII.	Do.	Inside of prop.	None.
VIII.	Decayed portion of lath brought up from the deep workings of the Northern Star Gold Mining Co., Ballarat. Had evidently been saturated with water for many years.	No portion was sound; all was burned and analyzed.	None.
IX.	Portion of sleeper used in a tramway, Northern Star Gold Mining Co., much decayed. A large quantity of water had been running over it for at least a year.	Do.	0.0129 grain.

A filter was constructed, consisting of a tinned-iron cylinder, about 3 in. in diameter and 6 in. long, terminating below in a funnel, inside of which was placed a filter of glass-wool, and above this the reducing-agents (animal charcoal, artificial iron and lead sulphides, roughly powdered). The upper part was connected by a rubber tube with the tap supplying the water to be tested.

The following preliminary test proved the efficiency of this filter: A solution in 400 gal. of water (from the Dunedin water-mains) of 28 lb. of common salt, 8 oz. of magnesium sulphate, 8 oz. of ferric chloride, and 0.1 grain of gold in the form of auric chloride, was allowed to trickle slowly through the filter, the operation taking about 48 hr. The mixture of sulphides and

charcoal was then removed, roasted, and assayed, when 0.0926 grain of gold was recovered, showing that practically all the gold had been precipitated.

In examining mine-waters, the water was first collected in an iron tank, and powdered alum was added to it, completely precipitating all suspended matter. After standing some hours, it was tapped from 2 or 3 in. above the bottom of the tank, and filtered as described.

Four samples were thus treated; but in no case was gold found.

The first sample (about 500 gal.) was water from the high-level tunnel of the Tipperary G. M. Co., which had percolated down from the surface through the lode-fissure for from 200 to 500 ft., and flowed in a large stream from the tunnel-mouth. This practically represented the vadose circulation only.

The second sample (about 500 gal.) was from the pump-discharge of the New Chum Railway Co., Bendigo, Victoria, and represented the whole drainage of the mine from the surface to a depth of 2,850 feet.

The third sample (about 700 gal.) was from the Long Tunnel G. M. Co.'s mine, Walhalla, Victoria, near a very rich lode, and represented the whole drainage between the adit (700 ft. below the summit of the hill) and a level about 2,300 ft. below the surface, or over 1,500 ft. below the adit.

The fourth sample (about 500 gal.), from a deep tunnel of the Premier mine, Advance Peak, Otago, driven on a lode which had proved richly auriferous in places, represented the whole drainage from the surface to probably 2,000 ft. below it.

The negative results of these tests are the more surprising to me, since other examinations, hereinafter described, afforded strong evidence that solution and re-precipitation of gold have taken place in the vadose region.

It is, of course, possible that gold may have existed in these samples in some form from which it was not precipitated by the reagents used. This is suggested, indeed, by my experience (see Chapter VII.) in attempting to precipitate gold from sea-water. The question can only be decided by the evaporation of samples (first freed from suspended matter) in larger amount and number than mine, and the assay of the residues. I venture to recommend such an inquiry to those who live in the vicinity of rich mines and have time for the work.

Does the Gold of the Vadose Region Contain Generally Less Silver than That of the Deep Circulation in the Same District?

Several investigations have seemed to prove that, on the average, the gold of the alluvial deposits in Australia and elsewhere is appreciably finer in quality than the vein-gold. The matter has been discussed chiefly in connection with the origin of nuggets;[22] but, so far as I know, no comparison as to fineness has been made between the vadose and the deep vein-gold.

The observed difference between placer- and vein-gold may be held to show, either that the oxidized mineral-bearing waters running in the ancient drift-deposits dissolved out part of the silver with which the gold was alloyed, or else that these waters dissolved both gold and silver, the gold being again precipitated, alloyed with less silver than before. Similar reasoning might be applied to an observed difference between the vadose and the deep zone, in the quality of vein-gold. I have therefore made comparative assays of this character in a number of cases.

The fineness of the gold may vary considerably even in the same level, and within a few feet. This is true even in such districts as Bendigo, Ballarat, and Otago, where the percentage of silver is comparatively low, while in districts like the Thames, N. Z., the variation observed is sometimes extraordinary. On the whole, however, the average quality of the gold won in districts of the former class varies little.

Five localities were chosen (chiefly by reason of facilities for obtaining specimens from near the surface), namely, (1) the Nenthorn gold-field, in mica-schist, in eastern Otago; (2) the Tipperary and Premier mines, in mica-schist, Macetown, central Otago; (3) the Dart river, in northern Gippsland, representing the Upper Silurian of Victoria; (4) the Bendigo field,[23] representing the Lower Silurian; and (5) the Thames district of the North Island, in altered Lower Tertiary andesite.

In a few instances the analyses were made of gold picked out of the reef; but the majority were assays of vein-stone.

[22] Professor Liversidge, in the paper already cited, gives a convenient summary of the literature of this subject.

[23] Surface-samples are hard to get in Bendigo. Nearly all the companies are mining in the deep region, and have long ago exhausted the pay-quartz above. I took many samples from outcrops of reefs, but found in the majority little or no gold. The results given below are those in which a prill of appreciable size was obtained by assaying 1,000 grains of vein-stone.

The percentage of silver was in each case obtained by difference, and represents the loss per cent. of the prill after quartation. The results were as shown in the table on p. 184.

These analyses of 76 samples go, on the whole, to prove that the average fineness of the gold in the vadose region is appreciably greater than in the deep circulation in the same district, and also that the vadose gold is considerably more regular in quality.

It seems to be indicated that considerable solvent action must have been exercised by water percolating through the rocks of the vadose region, as the denudation of the surface has gradually lowered the water-level, converting the deep circulation of former times into the vadose of to-day.

Analyses of Vadose Country-Rock, etc., at Different Distances from Auriferous Lodes.

At the beginning of this chapter I have pointed out the importance of separate rock-assays in the vadose region. It was relatively difficult to obtain good samples (other than surface-samples) of this class, because most of the mines are now deep, and the former long cross-cuts run on upper levels into the country-rock are abandoned and closed. The samples therefore comprise chiefly oxidized rock from pretty near the lodes, and 10 to 100 ft. below the surface, and surface-samples taken at all distances from the lodes. Particular interest attaches to samples of (1) oxide of iron and manganese deposited along bedding-planes or fractures; (2) solid rock as little altered as possible by the action of percolating water; and (3) secondary[24] sulphides, abundant in the vadose region of many mines.

The remarks covering the methods of concentration and assay pursued with samples from the deep levels, apply here also.

[24] In calling these vadose sulphides "secondary," I mean that they have probably been formed through the oxidization of the sulphides of the deep circulation by surface-water, followed by a reduction of the sulphates and re-precipitation of the sulphides by organic matter. I do not mean to say positively that the sulphides of the deep zone are not, as many observers believe, also secondary in this sense, that is, due to the reducing action of carbonaceous matter upon soluble sulphates. This is Sandberger's view (*Untersuchung*, etc., vol. i., p. 21). Yet so far as my experience of the deep sulphides goes, it certainly favors the theory of their formation by the action on the silicates of metals of hydrogen sulphide, dissolved in ascending water.

Relative Fineness of Vadose and Deep Vein-Gold.

A. Surface-Samples from Nenthorn Gold-Field, Otago, N. Z.

No.	Percentage of Gold.	Percentage of Silver.
1	91.85	7.15
2	89.27	10.73
3	90.43	9.67
4	89.19	10.81
5	92.01	7.99
6	89.38	10.62
7	91.46	8.54
8	90.79	9.21
9	90.07	8.53
10	92.00	8.00

Average fineness of 10 samples, 90.645 per cent. Range of fineness, 89.19 to 92.01 = 2.827 per cent.

B. From Deeper Levels of Nenthorn District (the Bulk of the Gold was Held by Pyrite).

No.	Percentage of Gold.	Percentage of Silver.
1	89.86	10.14
2	91.43	8.57
3	87.17	12.83
4	90.45	9.55
5	89.07	10.93
6	92.01	7.99
7	90.17	9.83
8	88.75	11.25
9	91.03	8.97
10	90.30	9.70

Average fineness of 10 samples, 90.024 per cent. Range of fineness, 87.17 to 92.01 = 4.84 per cent.

C. Surface-Samples from Tipperary Premier, and Sunrise Gold Mining Companies. All near Macetown, Central Otago, N. Z.

No.	Percentage of Gold.	Percentage of Silver.
1	96.12	3.88
2	93.37	6.63
3	94.19	5.81
4	92.87	7.53
5	95.00	5.00
6	94.58	5.42
7	93.23	6.77
8	95.84	4.16
9	95.93	4.07
10	94.89	5.11

Average fineness of 10 samples, 94.602 per cent. Range of fineness, 92.87 to 96.12 = 3.25 per cent.

D From Deep Levels (1,000 to 1,500 Ft. Below Surface) in Tipperary and Premier Mines, Macetown.

No.	Percentage of Gold.	Percentage of Silver.
1	95.39	4.61
2	94.48	5.52
3	91.87	8.13
4	96.29	3.71
5	93.06	6.94
6	94.31	5.69
7	93.80	6.20
8	94.73	4.27
9	93.90	6.10
10	94.10	5.90

Average fineness of 10 samples, 94.293 per cent. Range of fineness, 91.87 to 96.29 = 4.42 per cent.

NOTE.—A sample taken from a bar of 194 oz. from deep levels of Premier Gold Mining Co. contained 94.45 per cent.

E. Surface-Specimens from Richly Auriferous Lode in the Vicinity of the Dart River, North Gippsland, Victoria.

No.	Percentage of Gold.	Percentage of Silver.
1	91.87	8.13
2	94.96	5.04
3	93.08	6.92
4	92.00	8.00
5	92.63	7.37
6	94.73	5.27
7	93.45	6.55
8	95.01	4.99
9	94.91	5.09
10	92.84	7.18

Average fineness of 10 samples, 93.548 per cent. Range of fineness, 91.87 to 95.01 = 4.14 per cent.

F. Unoxidized Specimens from the Same Reef, Dart River, North Gippsland, Victoria.

No.	Percentage of Gold.	Percentage of Silver.
1	91.50	8.50
2	90.43	9.57
3	87.69	12.31
4 [a]	96.28	3.72
5	91.17	8.83
6 [b]	84.64	15.36
7	88.93	11.07
8	95.03	4.97
9	90.37	9.63
10	90.80	9.20

Average fineness of 10 samples, 90.984 per cent. Range of fineness, 84.64 to 96.28 = 12.36 per cent.

[a] Sample assayed consisted of arsenopyrite and pyrite.

[b] Sample assayed composed chiefly of galena.

Relative Fineness of Vadose and Deep Vein-Gold.—Continued.

G. Surface-Samples from Bendigo Gold-Field, Victoria.

No.	Percentage of Gold.	Percentage of Silver.
1	94.76	5.24
2	95.03	4.97
3	94.05	5.95
4	94.27	5.73
5	94.10	5.90
6	95.00	5.00

Average fineness of 6 samples, 94.535 per cent. Range of fineness, 94.05 to 95.03 = 0.98 per cent.

H. Samples from Deep Levels (1,200 to 3,000 Ft.) of Bendigo Gold-Field.

No.	Percentage of Gold.	Percentage of Silver.
1	93.08	6.92
2	95.04	4.96
3	94.00	6.00
4	91.27	8.73
5	91.30	5.70
6	94.19	5.81
7	93.96	6.04
8	92.95	7.05
9	92.37	7.63
10	94.70	5.30

Average fineness of 10 samples, 93.586 per cent. Range of fineness, 92.37 to 95.04 = 2.64 per cent.

I. Samples from Vadose Region of Various Parts of Thames District, N. Island, N. Z.

No.	Percentage of Gold.	Percentage of Silver.
1	63.72	36.28
2	79.34	20.66
3	52.90	47.10
4	57.39	42.61
5	67.01	32.99
6	59.98	40.02
7	65.55	34.45
8	73.07	36.93
9	60.08	39.92
10	51.19	48.81

Average fineness of 10 samples, 60.023 per cent. Range of fineness, 51.19 to 79.34 = 28.15 per cent.

K. Samples from Deep Circulation of the Thames District.

No.	Percentage of Gold.	Percentage of Silver.
1	63.76	56.24
2	71.14	28.86
3	59.93	40.07
4	53.01	46.99
5	64.25	35.75
6	43.17	56.83
7	66.98	33.02
8	51.30	48.70
9	69.04	30.96
10	48.75	51.25

Average fineness of 10 samples, 59.133 per cent. Range of fineness, 43.17 to 71.14 = 27.97 per cent.

[In the majority of cases the samples taken weighed 7 or 8 lb.; the samples tested, 4.48 lb.; and the assays were made from concentrates of the latter, but sometimes 4.48 lb. was the actual sample for assay; in which case the total quantity was pulverized to pass a No. 60 sieve, and divided into 12 parts of about 2,500 grains each, and to each part 3,000 grains of purified litharge, 2,000 grains of carbonate of soda, and 1,000 to 1,500 grains of borax were added for the assay, with sufficient argol to reduce about 400 grains of lead.]

But concentration of an oxidized rock is much more difficult, because oxidation destroys the heavy sulphides, and also liberates very finely divided gold, which there is danger of losing. Hence my results with vadose country-rock are not quantitatively correct. To minimize the probable error, the samples were not concentrated nearly as far as those from deep levels had been.

TABLE III.—*Analyses of Country-Rock from the Vadose Region of Walhalla Gold-Field, Gippsland, Victoria.*

Sample.	Approximate Distance from Auriferous Reef (Cohen's Reef).	Weight Examined.	Weight of Concentrates Obtained.	Percentage of Sulphur.	Yield of Gold.	Yield of Gold per Ton of Country-Rock.
	Feet.	Pounds.	Grains.		Grains.	Grains.
a.....	3 West.	4.48	1,904 Chiefly oxide of iron, showing a little mica.	Trace.	Nil.	Nil.
b.....	10 West.	4.48	1,650	Trace.	Nil.	Nil.
c.....	16 West.	2.24	1,824	Nil.	0.027	27.
*d**...	100 West.	2.24	All assayed	Nil.	Nil.	Nil.
e.....	240 West.	2.24	1,463	Nil.	0.0183	18.3
f.....	360 West.	1,000 g.	All assayed	Nil.	Nil.	Nil.
g.....	540 West.	4.48	1,280 Chiefly quartz, ferric oxide, with a little mica.	Nil.	0.0027	1.35
h.....	1,200 West.	2.24	1,640	Nil.	0.0076	7.6
i.....	6 East.	2.24	1,356 Mostly ferric oxide, with a little magnetite.	Nil.	0.029	29.
*j**....	75 East.	2.24	All assayed	Trace.	0.0017	1.7
k.....	360 East.	2.24	1,748 Chiefly ferric oxide	Nil.	Nil.	Nil.

a. Very hard, coarse-grained, solid sandstone, much stained with oxide of iron.
b. Fine-grained, hard, solid slate, very little altered in any respect.
c. Oxide of iron from a cavity between sandstone and slate. The country much broken near where sample was taken.
d. Slate, fine-grained, very little altered, very solid and hard.
e. Broken sandstone, slate, and oxide of iron, from a small fault in the rock, exposed to the surface.
f. White quartz, slightly iron-stained, from small reef-formation about 4 in. wide.
g. Hard, fairly coarse-grained sandstone, with seams of ferric oxide along the bedding-planes.
h. Slate, sandstone, and ferric oxide from broken country, filling a slight fault.
i. Ferric oxide, coating slate and sandstone.
j. Hard, solid, fine grained slate, little altered.
k. Hard sandstone, much stained with ferric oxide.
In the case of samples marked * the whole of the sample left after concentration was assayed after the concentrates had been examined.

Walhalla.—A good cross-section of the gold-bearing rocks of Walhalla is extended along both sides of the Walhalla creek, where the cliffs rise steeply from 300 to 600 ft. Analyses of specimens are given in Table III.

Ballarat.—A deep cutting, about 0.25 mile long, running east, across the strike of the rocks, from the summit of Sovereign hill, in this district, presented a good cross-section of the country-rock near the surface. Table IV. gives the result of analyses.

Otago.—Examinations of country-rock from the deep region in Otago were confined to one district, Macetown; but quartz reefs have been worked at various depths in different parts of the province; and vadose samples were taken from three other Otago districts besides Macetown, namely, Waipori, Nenthorn and Saddle Hill. In every case the country-rock is either phyllite or mica-schist. Table V. gives the analyses of 13 samples.

TABLE IV.—*Analyses of Country-Rock from the Vadose Region of the Ballarat Gold-Field, Victoria.*

Sample.	Approximate Distance from Auriferous Reef.	Weight Examined.	Weight of Concentrates Obtained.	Percentage of Sulphur.	Yield of Gold.	Yield of Gold per Ton of Country-Rock.
	Feet.	Pounds.	Grains.		Grains.	Grains.
a	8 East.	1.12	684 Mostly ferric oxide and quartz	Nil.	0.037	74
b	60 East.	2.24	1,050	Nil.	0.017	17
c	140 East.	4.48	1,812	Nil.	0.0063	3.15
d	186 East.	4.48	1,485	Nil.	0.0023	1.15
e	240 East.	4.48	2,116	Nil.	0.0016	0.8
f	360 East.	2.24	1,642	Nil.	0.0058	2.9
g	500 East.	1.12	856	Nil.	Nil.	Nil.

a. Oxide of iron, with a little quartz and loose sand, formed by the disintegration of sandstone.
b. Oxide of iron, from a joint separating two adjacent strata of sandstone.
c. Soft sandstone, pure white.
d. White pipe-clay, with yellow streaks. A product of the decomposition of slate.
e. Soft, fine-grained pipe-clay, colored from red to purple by oxide of iron.
f. Oxide of iron, mixed with soft sandstone and clay from broken country.
g. Oxide of iron, forming clay parting between two beds of pipe-clay.

Otago.—Samples from Districts Remote from Auriferous Lodes.—Vadose samples were also taken in Otago, far from any auriferous lodes. Previous assays having shown that the materials most likely to contain gold were the broken rock, iron oxide, etc., filling fault-fissures, the samples were taken of such materials only. If all the mica-schists of the Otago gold-field contained gold, some of it would be carried by percolating water into such crevices, and lodge there with the ferric oxide. The analysis of samples at a long distance from any auriferous reef is specially interesting, since, as will be seen in the last three tables, deposits of ferric oxide in the vadose region, even at a *considerable* distance from a reef, were nearly always auriferous.

A good section of the favorable rock (the middle division of the foliated schists already mentioned), in which, however, for several miles, no gold-bearing reef has yet been discovered, is exposed by the "Skipper's" road from Queenstown to Skipper's creek. This road is cut around almost vertical cliffs for several miles, on the north side of the Skipper's range. Nine samples of broken rock and ferric oxide from joints, cracks, and faulted country in these cuttings were analyzed, with the results shown in Table VI.

Lake Wakatipu.—Fourteen vadose samples of little-altered Upper Devonian and Carboniferous rocks were taken from the western shore of Lake Wakatipu. No gold was found in them. The examination is reported later on, under the head of "Gold in Marine Sediments."

TABLE V.—*Analyses of Rocks from the Vadose Region of Otago, New Zealand.*

Sample.	Distance from Auriferous Reef.	Approx. Depth Below Surface.	Locality.	Weight Taken.	Weight of Concentrates.	Percentage of Sulphur.	Yield of Gold.	Yield of Gold per Ton of Country-Rock.
	Feet.	Feet.		Pounds.	Grains.		Grains.	Grains.
a.....	4	40	From a tunnel driven along the Bella reef, Waipori, Otago.	4.48	643 Mostly mica and oxide of iron.	Nil.	0.0016	0.8
b.....	20	40	Do.....	4.48	1,246.....	Nil.	0.0107	5.35
c.....	3	50	Do.....	4.48	1,675.....	Nil.	0.065	32.55
d.....	60	30	Near the mouth of the low-level tunnel, Tipperary G. M. Co., Macetown, Otago.	4.48	1,217.....	Nil.	Nil.	Nil.
e.....	35	60	From the same tunnel, but 25 ft. nearer the reef.	2.24	1,176.....	Trace.	0.0179	17.9
f.....	20	70	From the same tunnel, 15 ft. nearer the reef.	2.24	1,030.....	Trace.	0.0086	8.6
g.....	160	35	From near the mouth of the low-level tunnel, Premier G. M. Co., Macetown, Otago.	1.12	774.....	Nil.	0.0018	3.6
h.....	90	85	From the same tunnel, but nearer the reef and at a greater depth.	2.24	617.....	Trace.	Nil.	Nil.
i.....	65	95	From the same tunnel, but 15 ft. nearer the reef.	2.24	612.....	Nil.	0.0013	2.6
j.....	6	40	From the Bonanza reef, Nenthorn, Otago, within 6 ft. of a rich auriferous reef.	2.24	1,738 Principally mica and ferric oxide.	0.027	0.0016	11.6
k.....	3	40	From the same mine, at the same depth, but nearer the reef.	2.24	1,247.....	Nil.	0.0073	7.3
l.....	600	20	From a cliff west of Saddle Hill reef, near Dunedin.	1.12	726.....	0.008	Nil.	Nil.
m.....	200	20	From the same locality, but nearer reef.	2.24	1,073.....	Nil.	0.0005	0.5

a, *b*, *c*. Mica-schist, yellowish color, soft, very much decomposed.
d. Hard mica-schist, with quartz bands 0.5 in. wide. Specimen much stained with oxide of iron.
e. Ferric oxide from a slight fault in mica-schist, showing a little quartz in veins.
f. Quartz and ferric oxide from broken country.
g. Solid mica-schist, much stained by ferric oxide.
h. Ferric oxide and broken mica-schist, from a small fault.
i. Solid mica-schist, much discolored by ferric oxide.
j, *k*. Much decomposed, very soft mica-schist, stained brown with ferric oxide.
l. Ferric oxide filling the space in joint-planes of phyllite, which forms the country-rock of this reef.
m. Decomposed phyllite, much stained with ferric oxide.

Ohinemuri District, Thames.—The samples collected for me from the vadose region in the Ohinemuri district, in the southern part of the Thames gold-field, differ somewhat from the oxidized samples of other gold-fields. All those analyzed are highly-altered andesites; and, in many cases, even when most oxidized, they contain much pyrite. This sometimes doubtless represents the pyrite found in the propylites of the deep region

TABLE VI.—*Analyses of Samples from Skipper's Road, near Lake Wakatipu, Otago.*

Sample.	Distance from Auriferous Reef.	Approx. Depth Below Surface.	Locality.	Weight Taken.	Weight of Concentrates.	Percentage of Sulphur.	Yield of Gold.	Yield of Gold per Ton of Country-Rock.
		Feet.		Pounds.	Grains.		Grains.	Grains.
a	At least 2 or 3 miles.	50	All these samples were taken from a deep cutting on the Skippers' road.	2.24	1,127 Chiefly ferric oxide and mica.	Nil.	Nil.	Nil.
b	About 0.25 mile from *a*.	80	.....	2.24	1,416 With a little pyrite.	Nil.	Nil.	Nil.
c	At least 1 mile.	30	.....	2.24	1,723.....	Nil.	Nil.	Nil.
d	About 1,000 yd. from *c*.	.....	.....	2.24	1,096 With a good percentage of sulph'd's.	1.384	Nil.	Nil.
e	From near sample *d*.	40	.....	2.24	834 Showed no pyrite.	Nil.	Nil.	Nil.
f	About 3 miles.	20	.....	2.24	1,568.....	Nil.	Nil.	Nil.
g	From near sample *f*.	40	.....	2.24	817.....	Trace.	Nil.	Nil.
h	Over 2 miles.	10	.....	1.12	716.....	Nil.	Nil.	Nil.
*i**	Near sample *h*.	15	.....	1.12	618.....	Nil.	Nil.	Nil.

a. Ferric oxide from joint-planes.
b. Broken rock; quartz and mica, with much contorted mica-schist, filling a fissure 18 in. wide.
c. Broken rock; quartz and mica.
d. Broken rock, but the sample contained a few large crystals of pyrite, somewhat decomposed to ferric oxide.
e. Broken rock, but showed no pyrite.
f. Quartz and broken mica-schist and ferric oxide, from a fault-fissure or lode-formation, about 1 ft. wide, in mica-schist.
g. Quartz and broken mica-schist.
h. Ferric oxide, filling joint-planes in broken mica-schist.
i. Quartz-interlaminations, about 2 in. wide, in mica-schist, much stained with ferric oxide.
In the case of sample marked * the whole of the sample left after concentration was assayed after the concentrates had been examined.

in this district; but, from the mode of its occurrence, I am inclined to think the greater part of it is due to the oxidation of the older pyrite to ferrous and ferric sulphate, and the subsequent reduction of such sulphates by organic matter. I have therefore called it "secondary" pyrite. (The bullion associated with it does not carry the abnormally high percentage of silver which was noticed in the bullion from the sulphides of the deep region—a fact which should repay further investigation, and might throw important light upon the solution and re-precipitation of gold and silver by natural agents.) Table VII. gives the results of the analyses of these samples.

TABLE VII.—*Analyses of Samples from the Vadose Region of the Ohinemuri District, Thames, New Zealand.*

Sample.	Depth Below Surface.	Approx. Distance from Reef.	Locality.	Weight Examined.	Weight of Concentrates.	Yield of Gold.	Yield of Gold per Ton.	Yield of Silver.	Yield of Silver per Ton.
	Feet.	Feet.		Pounds.	Grains.	Grains.	Grains.	Grains.	Grains.
a.....	10	30	From a cliff on the tramway between the Crown mine and Karangahake, Thames.	4.48	1,634.....	0.0014	0.7	0.0018	0.9
b.....	20	180	From a fault.	1.12	All assayed.	0.009	18	0.0036	7.2
c.....	20	350	From a fault.	4.48	1,065 With a good percentage of pyrite.	0.0062	3.18	0.0054	2.7
d.....	30	120	East of the Maria reef, Karangahake, Thames.	4.48	873 With a good proportion of pyrite.	Nil.	Nil.	Nil.	Nil.
e.....	80	3	Great Woodstock tunnel, Karangahake, Thames.	1.12	All assayed.	0.0095	19	0.0034	6.8
f.....	10	60	From a cliff on the Waitawheta river, near the Crown mine, Thames.	2.24	All assayed.	0.0013	1.3	0.0042	4.2
g.....	60	24	Near the Grace Darling reef, Waitekauri, Thames.	4.48	1,372.....	0.0063	3.15	0.0048	2.4
h.....	60	30	Foot-wall side of Crown reef.	4.48	846 With a large percentage of sulphides.	Nil.	Nil.	Nil.	Nil.
i.....	25	600	200 yd. off hanging-wall side of the Crown reef, 10 ft. above the Waitawheta river.	2.24	617 Nearly all pyrite.	0.0093	9.3	0.0126	12.6
j.....	10	660	From a fault exposed on the tramway between the Crown mine and Karangahake, Thames.	1.12	All assayed.	0.0071	14.2	0.0014	2.8

a. Nearly white propylite; showed a good percentage of pyrite.
b. Ferric oxide and higher oxides of manganese, with a little quartz.
c. Solid, hard andesite, oxidized to brown color on outside. Showed a good deal of pyrite.
d. Hard, greenish hypersthene-andesite. Showed a good deal of pyrite.
e. Ferric oxide and higher oxides of manganese, from a vein near the foot-wall of the Great Woodstock reef.
f. Andesite; brown, much decomposed. No pyrite visible.
g. Decomposed andesite and ferric oxide, from a fault.
h. Grayish-white andesite, much oxidized on the outside, but showing pyrite freely when broken.
i. Nearly white, very siliceous rhyolite. Showing pyrite freely.
j. Ferric oxide and higher oxides of manganese.

Remarks.—These examinations show a striking difference in gold-contents between the vadose and the deep region of the same district. Figs. 1 and 2 show this difference graphically, in curves plotted for the vadose samples and for samples from the deep region (900-ft. and 1,422-ft. levels) of the Walhalla Long Tunnel mine.

In the deep region, as has been shown, gold was obtained only when pyrite was present in the rock; and when such pyrite occurred at a considerable distance from the reef, it was seldom gold-bearing. In the vadose region, on the contrary, the country-rock was found to be impregnated with gold to a much greater distance from the reef, and to a much greater degree.

It is, of course, possible that some of the gold found in the vadose country-rock was carried into it mechanically by percolating surface-water, and its presence may therefore be no proof of the solution and re-precipitation of gold. But in view of the positions from which most of the samples were taken, I think the results indicate that such solution and re-precipitation have gone on to a considerable extent in the vadose region—the gold being in all probability derived from higher parts of the lode, which have long since disappeared through surface-detrition.

Chapter VII.—The Origin of Gold in Stratified Deposits.

The country-rocks of nearly all the chief Australian gold-fields are more or less altered sedimentaries, originally deposited in marine basins. Hence, writers on the origin of the gold in the reefs have laid much stress on the presence of minute quantities of gold and silver in sea-water. The argument is briefly:

Gold exists in sea-water. Palæozoic marine sediments therefore contained gold, either mechanically entangled in them, or precipitated with them by organic matter, which undoubtedly existed in the ancient seas. These horizontal deposits being subsequently tilted and fractured, their gold and silver were re-dissolved by percolating waters and re-precipitated in the lode-fissures where they are now found.

This has been the thesis of not a few ingenious speculations, backed sometimes by chemical equations, but not by chemical analyses.

In 1851, Malaguti and Durocher announced the discovery of silver in sea-water, and made a quantitative estimation of it, namely, 1 mg. in 100 l. (or 0.155 grain per ton). But they did not report any gold.

In 1872, E. Sonstadt[25] discovered gold in sea-water from Ramsey bay, on the coast of the Isle of Man. He did not determine the quantity, but said it was certainly less than 1 grain per ton. Strange to say, many writers who have used this discovery as a basis for theoretical speculation have represented Sonstadt as having found 1 grain per ton.[26]

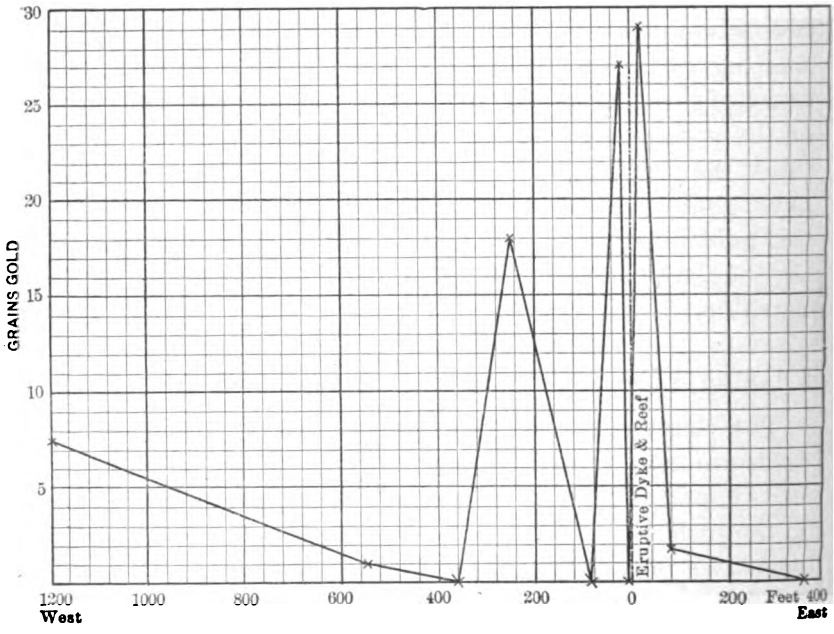

FIG. 1.—YIELD OF GOLD PER TON OF COUNTRY-ROCK IN VADOSE REGION.
(From Diagram 8 of Original Paper, Comparison of Yield of Vadose Region of Walhalla, Victoria, with Deep Circulation. See Tables III. and IV.)

So far as I am aware, no attempt has been made to verify Sonstadt's discovery, and to determine accurately the amount of gold in sea-water, or to test his statement that this gold is

[25] On the Presence of Gold in Sea-Water, *Chemical News*, vol. xxvi., No. 671, p. 159 (Oct. 4, 1872).

[26] Thus James Park in his report on the Thames Gold-Field [New Zealand *Mining Report* for 1893, Appendix] says (p. 65): "Sonstadt was the first to show that every ton of sea-water contains a grain of gold." A later writer, noting, perhaps, that Sonstadt found "less than a grain," is very scrupulous, and fixes the amount at 0.9 grain!

not precipitated by ordinary reducing-agents, by reason of the presence in sea-water of iodate of calcium.[27]

Methods of Detecting Gold in Sea-Water.

Sonstadt's Methods.—Sonstadt gave three methods for the detection of gold in sea-water, two of which he recommended as easily applicable. In the first of these, 150 to 200 cc. of sea-

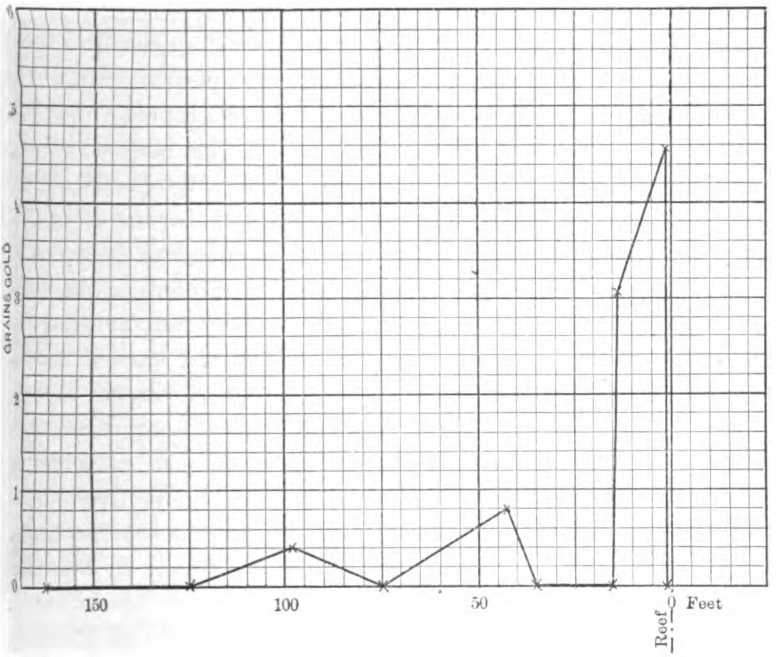

FIG. 2.—YIELD OF GOLD PER TON OF COUNTRY-ROCK AT 900-FT. LEVEL AND 1,422-FT. LEVEL.

(From Diagram 9 of Original Paper, Comparison of Yield of Vadose Region of Walhalla, Victoria, with Deep Circulation. See Tables III. and IV.)

water is acidulated with hydrochloric acid, ferrous sulphate is added, and the water is concentrated by boiling. The film of ferric oxide found in the bottom of the dish is treated with

[27] Since my experiments were made, I have learned from Mr. Rickard's paper On the Origin of the Gold-Bearing Quartz of the Bendigo Reefs (*Trans.*, xxii., 308) that Münster has found gold in the sea-water of Christiania fiord, and has estimated the amount. I find also that Prof. A. Liversidge has estimated that the sea-water off the coast of N. S. Wales contains 0.5 grain of gold to the ton. (See his paper, read before the N. S. W. Royal Society, Oct. 2, 1895, On the Amount of Gold and Silver in Sea-Water.)

chlorine-water, and the solution obtained is tested for gold with tin chloride. In the second method, a small quantity of baric chloride is added to the sea-water, and both gold and silver are found to be precipitated.

The first method I tried upon water from the Pacific, at St. Clair head, near Dunedin, and obtained with tin chloride a distinct coloration, doubtless due to gold.[28] But I found it impossible to obtain beads of gold by fusing with borax and pure lead, as Sonstadt directs. (This is not surprising, since my subsequent determinations would give, as the quantity of gold in 200 cc. of this sea-water, less than 0.000012 grain.) The necessity of boiling makes this method unsuitable for the treatment of samples large enough to yield a weighable bead of gold.

I therefore tried the precipitation with baric chloride. Sonstadt makes the remarkable assertion that in order to precipitate the gold, the baric chloride does not need to be added in sufficient quantity to precipitate as baric sulphate all the soluble sulphates in the sea-water, but, on the contrary, that the amount added to a liter of sea-water need not exceed that required to form about 1 grain of precipitate. Baric sulphate being one of the least soluble of salts, this statement seems inexplicable; nevertheless, I have been convinced, whatever be the explanation, that Sonstadt's method is as effective as if the whole of the soluble sulphates were precipitated as baric sulphate.

He explains the precipitation by baric chloride by supposing the gold to be present as an aurate. To test this question, artificial sea-water was prepared, and the aurate of potassium was added to it. Subsequent treatment with baric chloride precipitated no gold. The experiment was repeated, with the same result.

It seems unlikely, therefore, that the gold exists in sea-water as an aurate. I confess that I can form no conception of its state of combination. The subject would repay a more thorough investigation.

The Author's Method.—Having been led, by evidence which I will not here repeat, to doubt whether the precipitation with baric chloride was complete, I tried a different one, which, if

[28] The experiment is more successful with the modification of the tin chloride test prepared by T. K. Rose, *Chemical News*, vol. lxvi., No. 1723, p. 271 (Dec. 2, 1892).

successful at all, would certainly precipitate all the gold present. All ordinary salts of gold are reduced to the metallic state by moderate heating. Applying this principle first to an artificial solution, I added to 112 lb. of artificial sea-water[29] ten times as much calcic iodate as Sonstadt found, and a solution of auric chloride in sodium chloride, containing 0.005 grain of gold, so that the water would contain 0.1 grain of gold per ton. This solution was allowed to stand in a dark place for a week, that the gold might have time to form possible new combinations. The whole was then evaporated; the mixed salts (over 4 lb.) were heated dull red and lixiviated with water; the insoluble residue (123 grains) was fused with borax and pure litharge, and 0.0043 grain of gold was obtained. The experiment was repeated, the gold being added as an iodate, dissolved in excess of potassic iodate; and in this case 0.0052 grain of gold was recovered. (The slight excess may have been due to a small particle of the cupel remaining in the button. It was not due to silver in the litharge.)

The method was then applied to actual sea-water; only the sample was doubled in weight, to allow for the smaller proportion of gold. The mixed salts (about 8 lb.) resulting from the evaporation of 0.1 ton of sea-water were heated dull red and lixiviated, and the residue (principally sand, with a little oxide of iron) was fused and cupelled as before. The weight of pure gold obtained from 0.1 ton of sea-water was, in the first experiment 0.0065, and in the second 0.0071 grain. In both cases, the prill contained absolutely no silver.

The following table summarizes the experiments above described:

Determinations of Gold in Sea-Water.

Method.	Sea-Water.	Gold Obtained.	Gold per Ton.
1. Sonstadt's (baric chloride):	Pounds.	Grain.	Grain.
a. All sulphates precipitated	224	0.0061	0.061
	112	0.0038	0.076
b. Small proportion of sulphates precipitated	224	0.0074	0.074
	224	0.0078	0.078
2. Evaporation and reduction of gold in residue by heating	224	0.0065	0.065
	224	0.0071	0.071
Average per ton			0.071

[29] Prepared according to the analysis by Roscoe and Schorlemmer.

I have said nothing concerning the silver in sea-water. Precipitation by baric chloride certainly saves some silver, but only about one-fourth as much as was reported by Malaguti and Durocher. Probably the precipitation is not complete.

The Precipitation of Gold in Marine Sediments.

Since gold exists in sea-water, it seems reasonable to believe that it is precipitated at the present time by natural reducing-agents. Those writers who trace the metallic contents of lodes to metals dissolved in sea-water assume, indeed, that such a precipitation is constantly going on; but experimental proof of this assumption is lacking. I have attempted to investigate the question in two ways:

1. By the examination of coast-sediments, now being deposited under conditions favorable to the reduction of gold from the sea-water.

2. By the introduction into sea-water of reducing-agents such as naturally occur along the coasts at the present time, and a subsequent examination for precipitated gold.

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In each case, from 1 to 2 cwt. of the silt was carefully panned off, till a residue of about 1,000 grains was left. This residue consisted chiefly of magnetite, augite, and hornblende, derived from the volcanic rocks of the coast. The percentage of sulphur (insoluble sulphides) in the concentrate was determined upon a small portion, and the remainder was roasted (giving in every case a strong reaction of sulphur dioxide).[30] The roasted material was then assayed. The details of four assays are given in the following table:

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	Grains.	Grains.	Per Cent.	
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The results are given in the following table:

[30] When the magnetite was removed by means of a magnet, the remainder did not show, under the microscope, recognizable crystals of pyrite; but the presence of pyrite was certainly proved by roasting, and by the sulphur-determination.

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Sample.	Description.	Weight Burned.	Results.
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Attempts to Precipitate Gold from Sea-Water.

These experiments were confined to such natural reducing-agents as might naturally occur along the coast at the present day, namely, sulphides of iron (chiefly formed by the reduction of the sulphates of sea-water), and carbonaceous matter of various kinds.

To make a suitable filter, an earthenware pipe 4 in. in diameter and 1 ft. long was closed at the ends with strong cloth. Next the cloth was placed a loose plug of asbestos, about 2 in. in thickness, wrapped in linen, and the middle part of the pipe was filled with coarsely-broken earthenware, with which the reducing-agent was mixed. The reducing-agents used were animal charcoal, wood-charcoal, soot, and sulphides of iron, copper, and lead—the latter being prepared by precipitating sulphates of iron and copper and the nitrate of lead, in order to make sure that they should contain no gold.

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The results are given in the following table:

Experiments in Reducing Gold from Sea-Water.

Experiment.	Reducing-Agent.	Remarks.	Gold Found.
a.	Animal charcoal, in fine powder.	The greater part of the animal charcoal had been washed through the filter.[a] The remainder was assayed.	Nil.
b.	Mixture of pounded charcoal and soot.	The smaller particles washed away. Charcoal remained.	Nil.
c.	Animal charcoal in lumps.	.....	Nil.
d.	Sulphide of iron.	The sulphide was much oxidized; the whole apparatus being coated with ferric oxide.	Nil.
e.	Sulphide of lead in lumps.	Very little altered.	Nil
f.	Sulphide of copper in lumps.	Carbonate of copper found in the asbestos filter and other parts of the apparatus.	Nil.
g.	Mixture of animal charcoal, soot, sulphide of lead, sulphide of copper, and sulphide of iron.	Very little oxidation, even of the artificial sulphide of iron, was noticed.	Nil.

[a] After the first two attempts the reducing-agents were put in, not as powder, but in lumps from 0.25 to 0.5 in. in diameter, it having been found that the strong current carried the finer stuff through the asbestos filter.

A very large quantity of sea-water must have passed through the apparatus in each of the above cases, but there was no way of estimating it with precision. In view of the negative results of all the experiments, an attempt was made to precipitate gold and silver from a measured quantity of sea-water. Ten thousand grains of artificial sulphides of iron, copper, and lead, with animal charcoal and wood-charcoal—all in fine powder—were mixed in a barrel with 60 gal. of sea-water taken from the Pacific ocean at Tomahawk Head, near Dunedin. The reducing-agents were stirred in the water for half an hour, and the sediment was allowed to settle for some hours. The clear water above was then decanted off, and the barrel was again filled. This operation was repeated 14 times in the same barrel, or until over 4 tons of sea-water had been treated. The sediment was then collected and roasted at a dull red heat, to incinerate the charcoal and get rid of the sulphur. On assaying the residue, no gold was obtained; but the result was a

bead of pure silver weighing 0.0014 grain. I cannot say certainly whether this silver (which contained no gold) came from the sea-water or from the litharge used. I do not think the latter. If it came from the sea-water, however, it is noteworthy that the amount from 4 tons represents only 0.00035 grain per ton, or one five-hundredth part of the quantity found in sea-water by Malaguti and Durocher in 1851.

All my experiments have thus signally failed to show any precipitation of gold (and have practically failed as to silver) from sea-water by natural reagents. So far as they go, they lend no support to the theory that the deposition of gold and silver by such reagents in marine sediments is now going on.

If such deposition had been the rule in former periods, and if this be the origin of the gold in stratified formations, why should only a comparatively small proportion of such formations be traversed by auriferous veins? This point has not escaped the attention of Posepny.[31] It seems to me that important evidence may be drawn from the examination of stratified rocks known to be consolidated marine sediments, but the lodes in which have not proved auriferous. Table VI. gives an examination of nine samples from Skipper's road, east of Lake Wakatipu, Otago, an area in which the rocks are known to belong to the middle division of the foliated mica-schists (the favorable country-rock for gold in Otago), but in which no auriferous reefs had hitherto been discovered. Only those parts (*e. g.*, fillings of veins and seams, etc.) particularly favorable to the deposition of gold were examined, but no gold was found in any of the samples.

A second series of examinations was made on samples from the west shore of Lake Wakatipu, which is largely occupied by rocks of the Maitai (Carboniferous) and the Te Anau (Upper Devonian) series. These rocks (mostly sandstones and slates) are undoubted marine sediments, but no gold has been found in this area.

If the gold of the lodes in the foliated mica-schists east of this lake was originally deposited from sea-water and has since been collected by lateral segregation, it is difficult to understand why gold should not have been deposited in the marine sediments west of the lake also.

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[31] Genesis of Ore-Deposits, *Trans.*, xxiii., 307 (1893).

I therefore examined 16 samples of quartz, ferric oxide, etc., from the two series above named, where they are exposed north and south of the Greenstone river. There were 4 samples of fine-grained blue slate; 6 of ferric oxide from joints and fissures; 4 of small quartz veins, none of which contained sulphides; 2 of slate containing large crystals of pyrite, amounting in weight to 254 grains for the two samples.

No trace of gold or silver was found in any of these samples.

Chapter VIII.—Summary of Results.

[The recapitulation of the various results recorded in the preceding chapters is here omitted, to save space.]

Bearing of these Results on the Origin of Auriferous Lodes.

When I began this work, seven years ago, I was strongly inclined to believe that the lateral-secretion theory afforded the most reasonable explanation of the origin of auriferous deposits in these colonies; but, as the result of each series of examinations appeared, I was forced to the following conclusions:

If any reliance can be placed on the examinations detailed in the foregoing chapters, they seem to indicate that the gold of many lodes of the chief mining-districts of New Zealand, Victoria, and Queensland is due, not to lateral segregation from the adjacent country-rock, but to solutions ascending from some rock deeper than any now exposed at the surface in any part of these colonies.

I am not concerned with the question whether this source is the vague "barysphere," with its somewhat apocryphal contents of heavy metals. I have simply to note that a series of laborious and careful examinations has failed to find it in the rocks of the "lithosphere."

What may be the value of these investigations in the study of the general question of the origin of ore-deposits I leave the reader to judge, being myself content to quote the opinion of Professor Stelzner, of Freiberg, no mean investigator of that larger question, that

"Each increase of our positive knowledge of the nature and mode of origin of ore-deposits, each explanation of any question connected with such deposits or with their associated country-rocks, is a distinct gain, not only to science, but also to mining practice." [32]

[32] Concluding sentence of *Die Lateralsecretionstheorie* (1889).

Discussion.

(*Trans.*, xxvii., 993.)

Joseph Le Conte, Berkeley, Cal.: I have read with some care and with extreme interest the work of Dr. Don, and have no hesitancy in expressing my high estimate of its value. We have here an example of laborious work undertaken in the true scientific spirit and by right methods. Loose statements and rash conjectures are here brought to the test of chemical analyses. By such work only may we hope to reach reliable conclusions and finally to solve our complex problems presented by the concurrence of ore-deposits.

Such work as this is not only scientific but is in the highest degree practical; for while a crude and imperfect science, by interfering with the results of approved empirical methods, may be positively hurtful, a more perfect science must eventually become the only sure guide to practice. Such a more perfect science can only be reached by such work as Dr. Don's.

I am sure every member of the Institute will unite with me in the hope that Dr. Don will continue his work, and that his example will incite others to similar work.

S. F. Emmons, Washington, D. C.: I desire to bear my humble testimony to the great value of Dr. Don's paper to the science of ore-deposits, the thoroughness and accuracy of his work, and the immense amount of care-taking and tedious labor which it represents. The only regret with regard to it is that it could not have been published in full. No more important paper in its line has ever appeared in the *Transactions*. Indeed, this is a line in which far too little has been done anywhere. Geologists are not often sufficiently trained chemists to carry on such work, if they had the time; and for mining-geologists in our country the press of work in other directions is so great that they could not give the necessary time involved in this class of work, if they were so inclined. The chemist, on the other hand, is rarely enough of a geologist, or so placed, as to get sufficient field-experience to keep thoroughly in touch with the processes of nature as shown in mine-workings. By an organization like the U. S. Geological Survey, where the chemist and the geologist might work in harmony for a common purpose, it would seem that investiga-

tions into terrestrial chemistry might best be carried on; and 15 years ago, in connection with Mr. Hillebrand, one of the most thorough inorganic chemists of the day, I had planned such a line of experimental work, which I hoped might be continued as part of the regular chemical work of the Survey. But the powers that were willed it otherwise. My colleague, Mr. Becker, has made some important researches in this line, especially with regard to the natural solvents of gold, which do not appear to have come under Mr. Don's notice. Such work is necessarily very slow, and Mr. Don's paper, as he tells us, covers the results of seven years' labor.

I do not propose to discuss Mr. Don's paper from a chemical point of view, but only to consider the deductions that may be made from it from the geological side; and I do this with some hesitation, because, not being able to read his statements in detail, I may not infer correctly what his actual conclusions were. I must say, however, that he seems to be most broad-minded in this respect, and his work presents a pleasing contrast to parts of the great paper of the lamented Posepny, where the effects of the latter's recent contest with Sandberger seemed to make him look at Nature through *ascensionistically* colored glasses.

Dr. Don's first and most important conclusion from his tests is that gold does not occur in the rocks of the regions investigated by him as an original constituent of the bisilicates, and that where it is found in these rocks it is associated with sulphides, mainly of iron. His inference seems to be that it cannot be original in the rock, because pyrite is necessarily a secondary constituent, that is, one introduced after the rock consolidated. Now, my work for the past ten years has been bringing me more and more to doubt the adequacy of the bisilicates of eruptive rocks as a source of the metals for our ore-deposits, and, especially in the case of gold, to look to the pyrite, if not as a source, as the visible accompaniment. Where there is no pyrite in the neighboring eruptive rocks, I have not found that the veins are usually rich. But I have not, therefore, abandoned my belief that eruptive rocks, similar to those we see at the surface, are the source of supply from which the great majority of our ore-deposits have been concentrated. Pyrite is not necessarily a secondary constituent in such rocks,

as seems to be tacitly assumed by many. On the contrary, most petrographers admit the existence of primary pyrite, though they do not generally appreciate its importance in the study of ore-deposits. Lindgren has lately discussed primary pyrites as a product of magmatic consolidation in the gold-bearing rocks[33] of California. I cannot even feel absolutely sure, in spite of the apparent conclusiveness of Mr. Don's investigations for his regions, that the bisilicates of our Rocky Mountain eruptives may not contain some of the metals, but must wait until similarly exhaustive tests have been carried on here. Lead and cobalt have been found by Mr. Hillebrand in the bisilicates of some of the eruptive rocks of the Ten-Mile district, and lead and silver similarly by Mr. Eakins in the bisilicates of granite at Silver Cliff, Colo.

It seems important to note that the lateral-secretion theory which Mr. Don's tests seem to disprove is not the one that has been generally advocated in the United States; for I fancy few American geologists believe in the narrower view advocated by Sandberger, that the metals are derived necessarily from the immediately adjacent country- or wall-rock. Dr. Don says that he believes the gold of New Zealand is derived from rocks deeper than any now exposed at the surface there, but adds that he "is not concerned with the question whether this source is the vague barysphere, with its somewhat apocryphal contents of heavy metals." While, therefore, no longer a believer in Sandberger, he is apparently not willing to subscribe to the extreme views of Posepny. It has been the fashion for some time to decry Sandberger; but I think his work has been of the utmost value to the study of ore-deposits, even if his ultimate conclusions are not admitted; for he aroused us from the unthinking belief that the metals necessarily came from unknown depths, which it was fruitless to speculate about or to try to investigate. He started in movement the pendulum of thought, which had so long been stationary at that point; for a while it swung on his side, then back again to the ascensionist side. Now, with some geologists, it has taken a very strong impetus in the direction of the long-ago abandoned sublimation theory, or something very like it. The Swedish geolo-

[33] Gold Quartz Veins of Nevada City and Grass Valley, by W. Lindgren, *Seventeenth Annual Report, U. S. Geological Survey*, Part II., p. 94 (1895–96).

gists represented by Vogt, a disciple of the great petrographer Brögger, consider certain workable masses of iron and other ores as segregations from the still molten mass, or direct products of magmatic differentiation. Other minerals occurring in pegmatite veins, and some metallic oxides, like tin, for instance, they consider to have been deposited in the last stages of consolidation of a molten magma by a mixed process, which they call pneumatolysis, and which brings in the agency of water expelled during cooling from the igneous magma. This comes back to the old French theory of aqueo-igneous fusion in the presence of certain substances, such as fluorine, boron, chlorine, etc., which were called *agents minéralisateurs;* but it is less purely theoretical, in that it is founded on certain facts of observation in nature.

Vogt is at present preparing a new book on ore-deposits, in which he will doubtless extend very widely the scope of his pneumatolytic processes. But the applicability of either the French or the Swedish theory must be limited by a very simple geological condition, which is—whether the fissures in which ore-deposition has taken place could have been formed during the final consolidation of the eruptive magma. In most of the important ore-deposits which I have had opportunities of studying, the fissures or fractures which have served as ore-channels were the result of earth-movements that took place long after the entire consolidation of the eruptive magmas. In some cases, even, there is evidence of several such movements before the ore-deposition. My belief, as I have had occasion to state already, is that, by reason of some process which, for want of a better name, we may call magmatic differentiation, certain portions of an eruptive mass are richer in metals than the average; and that from such portions circulating solutions have abstracted these diffused metals and deposited them in a more concentrated form in favorable situations in rocks in the vicinity. The original bringing up of the metals from the bathysphere was, however, accomplished by the eruptive magma before consolidation. Present ore-deposits are in this sense the result of a secondary concentration at only moderate depths.

Dr. Don's investigation of the processes going on, or that may go on, in the vadose region affords interesting and useful data. He first assumes that deposits are generally richer in the pre-

cious metals above than below the water-line—a perfectly justifiable assumption, in my opinion—and then presents alternative explanations, one based on the ascension, the other on the lateral-secretion, theory; but he does not mention the most obvious explanation of this fact, namely, that the baser metals, which are usually in far greater amount than the precious metals, form by oxidation more readily soluble compounds, and are therefore to a much larger extent removed in the vadose or oxidizing region, while the precious metals are for the most part either not dissolved or are re-precipitated. Hence, the specific gravity of the whole mass of vein-material is decreased in the vadose region; and a given bulk, though it may have absolutely no more of the precious metal in it than before oxidation, contains a relatively higher percentage, by weight, of the precious metals. There may also be in places an actual enrichment, due to the ready precipitability of the precious metals. I have myself seen cases where, in a zone immediately above the water-line, the ore-body was not only very much richer than in the unoxidized portion below, but also richer than the average of the oxidized ore above, showing that the precious metal had been in a measure leached down and re-precipitated. Dr. Don himself shows various ways in which gold might be dissolved in the vadose region and re-precipitated lower down; he also thinks it may have been carried down mechanically; the result of his investigations of mine-waters being that, where they are found to contain gold, it is usually in mechanical suspension rather than in solution.

One of the most interesting parts of Dr. Don's investigations is that relating to the gold-content of sea-water, in which he has not contented himself with the vague statement that the metal does occur, but has made a quantitative estimate of its amount, which must be translated into the metric system in order to become intelligible to any but English chemists. The average content as determined by him is 0.0071 grain to the ton, which means, if I have calculated correctly, something like twelve million dollars' worth to the cubic mile—a large sum, if it could be gotten out. But Dr. Don has shown by a pretty exhaustive series of experiments that there is no probability that any natural precipitant would throw down any measurable portion of it.

GEORGE F. BECKER, Washington, D. C.: Dr. Don's paper is an extremely important contribution to mining-geology, and worth the vast amount of labor which it has manifestly cost. I trust that the paper in the *Transactions* will prove to be only a preliminary abstract, and that the entire *mémoir* will soon appear.

The greater part of the conclusions which Dr. Don reaches are quite in line with those to which Mr. Lindgren and I have been led by studies of the gold-deposits in this country.[34] I have been greatly impressed of late years with the character of the auriferous wall-rocks of gold-quartz veins. It seems to be true in most cases, for deep mines, that the gold in the walls is contained in the sulphurets; that it is of smaller fineness than the vein-gold; that the sulphurets are pyrites; and that gold and sulphurets diminish rapidly in quantity as the distance from the vein increases. Sometimes the wall-rock pyrite is almost barren. There appear to me to be two sorts of wall-pyrite. One seems to be the result of the action, on ferro-magnesian silicates, of the sulphides of hydrogen or of the alkalies, as I pointed out in treating of the Comstock lode. This variety is sometimes, and I suspect usually, almost worthless. There are other impregnations of pyrite which seem to me to have permeated from the vein-fissures, in solution, as double sulphides of the alkalies and iron. I have studied such solutions in a *mémoir* on quicksilver-deposits, and shown that solutions of alkaline carbonates, partly charged with hydrogen sulphide, will take up notable quantities of many sulphurets, and also of gold. Dr. Don has, I think, overlooked this investigation. Mr. Dölter has since succeeded, where I failed, in dissolving lead and silver sulphides in a similar menstruum.

Wall-rocks appear to be much more permeable by solutions of some substances than by those of others. Native gold, quartz, and all the sulphurets excepting pyrite, are for the most part retained in the veins, while carbonates seem to penetrate freely into the wall-rock. This indicates an osmotic separation of the metal-bearing solution, as I pointed out years ago.

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[34] Parts of these studies have been printed in the *Fourteenth to Eighteenth Annual Reports, U. S. Geological Survey* (1892–96).

I have said nothing concerning the silver in sea-water. Precipitation by baric chloride certainly saves some silver, but only about one-fourth as much as was reported by Malaguti and Durocher. Probably the precipitation is not complete.

The Precipitation of Gold in Marine Sediments.

Since gold exists in sea-water, it seems reasonable to believe that it is precipitated at the present time by natural reducing-agents. Those writers who trace the metallic contents of lodes to metals dissolved in sea-water assume, indeed, that such a precipitation is constantly going on; but experimental proof of this assumption is lacking. I have attempted to investigate the question in two ways:

1. By the examination of coast-sediments, now being deposited under conditions favorable to the reduction of gold from the sea-water.

2. By the introduction into sea-water of reducing-agents such as naturally occur along the coasts at the present time, and a subsequent examination for precipitated gold.

Examination of Coast-Sediments.—To secure trustworthy results, the whole of the drainage-basin to the erosion of which the sediments are due should consist of non-auriferous rocks, so that we may be sure that any gold detected did not come from the land. Otago harbor, on the upper part of which Dunedin is located, satisfies this requirement. The Leith and other small streams entering the harbor flow wholly through basic Tertiary volcanic rocks which contain no gold. At the same time the shores are more or less covered with timber, so that organic matter is abundant in the sediments of the streams. The volcanic rocks contain much iron. Beds of hematite and limonite abound along the shores. The conditions for the reduction of gold from sea-water are therefore very favorable. Besides organic matter, there is sulphide of iron, produced by the action of the sulphates in sea-water upon iron-salts, forming sulphate of iron, reducible to sulphide by organic matter. (As will be seen, some such action does in fact take place. In every case the concentrates contained insoluble sulphides.)

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c.	Animal charcoal in lumps.	.....	Nil.
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e.	Sulphide of lead in lumps.	Very little altered.	Nil
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g.	Mixture of animal charcoal, soot, sulphide of lead, sulphide of copper, and sulphide of iron.	Very little oxidation, even of the artificial sulphide of iron, was noticed.	Nil.

[a] After the first two attempts the reducing-agents were put in, not as powder, but in lumps from 0.25 to 0.5 in. in diameter, it having been found that the strong current carried the finer stuff through the asbestos filter.

A very large quantity of sea-water must have passed through the apparatus in each of the above cases, but there was no way of estimating it with precision. In view of the negative results of all the experiments, an attempt was made to precipitate gold and silver from a measured quantity of sea-water. Ten thousand grains of artificial sulphides of iron, copper, and lead, with animal charcoal and wood-charcoal—all in fine powder—were mixed in a barrel with 60 gal. of sea-water taken from the Pacific ocean at Tomahawk Head, near Dunedin. The reducing-agents were stirred in the water for half an hour, and the sediment was allowed to settle for some hours. The clear water above was then decanted off, and the barrel was again filled. This operation was repeated 14 times in the same barrel, or until over 4 tons of sea-water had been treated. The sediment was then collected and roasted at a dull red heat, to incinerate the charcoal and get rid of the sulphur. On assaying the residue, no gold was obtained; but the result was a

bead of pure silver weighing 0.0014 grain. I cannot say certainly whether this silver (which contained no gold) came from the sea-water or from the litharge used. I do not think the latter. If it came from the sea-water, however, it is noteworthy that the amount from 4 tons represents only 0.00035 grain per ton, or one five-hundredth part of the quantity found in sea-water by Malaguti and Durocher in 1851.

All my experiments have thus signally failed to show any precipitation of gold (and have practically failed as to silver) from sea-water by natural reagents. So far as they go, they lend no support to the theory that the deposition of gold and silver by such reagents in marine sediments is now going on.

If such deposition had been the rule in former periods, and if this be the origin of the gold in stratified formations, why should only a comparatively small proportion of such formations be traversed by auriferous veins? This point has not escaped the attention of Posepny.[31] It seems to me that important evidence may be drawn from the examination of stratified rocks known to be consolidated marine sediments, but the lodes in which have not proved auriferous. Table VI. gives an examination of nine samples from Skipper's road, east of Lake Wakatipu, Otago, an area in which the rocks are known to belong to the middle division of the foliated mica-schists (the favorable country-rock for gold in Otago), but in which no auriferous reefs had hitherto been discovered. Only those parts (*e. g.*, fillings of veins and seams, etc.) particularly favorable to the deposition of gold were examined, but no gold was found in any of the samples.

A second series of examinations was made on samples from the west shore of Lake Wakatipu, which is largely occupied by rocks of the Maitai (Carboniferous) and the Te Anau (Upper Devonian) series. These rocks (mostly sandstones and slates) are undoubted marine sediments, but no gold has been found in this area.

If the gold of the lodes in the foliated mica-schists east of this lake was originally deposited from sea-water and has since been collected by lateral segregation, it is difficult to understand why gold should not have been deposited in the marine sediments west of the lake also.

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[31] Genesis of Ore-Deposits, *Trans.*, xxiii., 307 (1893).

I therefore examined 16 samples of quartz, ferric oxide, etc., from the two series above named, where they are exposed north and south of the Greenstone river. There were 4 samples of fine-grained blue slate; 6 of ferric oxide from joints and fissures; 4 of small quartz veins, none of which contained sulphides; 2 of slate containing large crystals of pyrite, amounting in weight to 254 grains for the two samples.

No trace of gold or silver was found in any of these samples.

Chapter VIII.—Summary of Results.

[The recapitulation of the various results recorded in the preceding chapters is here omitted, to save space.]

Bearing of these Results on the Origin of Auriferous Lodes.

When I began this work, seven years ago, I was strongly inclined to believe that the lateral-secretion theory afforded the most reasonable explanation of the origin of auriferous deposits in these colonies; but, as the result of each series of examinations appeared, I was forced to the following conclusions:

If any reliance can be placed on the examinations detailed in the foregoing chapters, they seem to indicate that the gold of many lodes of the chief mining-districts of New Zealand, Victoria, and Queensland is due, not to lateral segregation from the adjacent country-rock, but to solutions ascending from some rock deeper than any now exposed at the surface in any part of these colonies.

I am not concerned with the question whether this source is the vague "barysphere," with its somewhat apocryphal contents of heavy metals. I have simply to note that a series of laborious and careful examinations has failed to find it in the rocks of the "lithosphere."

What may be the value of these investigations in the study of the general question of the origin of ore-deposits I leave the reader to judge, being myself content to quote the opinion of Professor Stelzner, of Freiberg, no mean investigator of that larger question, that

"Each increase of our positive knowledge of the nature and mode of origin of ore-deposits, each explanation of any question connected with such deposits or with their associated country-rocks, is a distinct gain, not only to science, but also to mining practice." [32]

[32] Concluding sentence of *Die Lateralsecretionstheorie* (1889).

Discussion.

(*Trans.*, xxvii., 993.)

Joseph Le Conte, Berkeley, Cal.: I have read with some care and with extreme interest the work of Dr. Don, and have no hesitancy in expressing my high estimate of its value. We have here an example of laborious work undertaken in the true scientific spirit and by right methods. Loose statements and rash conjectures are here brought to the test of chemical analyses. By such work only may we hope to reach reliable conclusions and finally to solve our complex problems presented by the concurrence of ore-deposits.

Such work as this is not only scientific but is in the highest degree practical; for while a crude and imperfect science, by interfering with the results of approved empirical methods, may be positively hurtful, a more perfect science must eventually become the only sure guide to practice. Such a more perfect science can only be reached by such work as Dr. Don's.

I am sure every member of the Institute will unite with me in the hope that Dr. Don will continue his work, and that his example will incite others to similar work.

S. F. Emmons, Washington, D. C.: I desire to bear my humble testimony to the great value of Dr. Don's paper to the science of ore-deposits, the thoroughness and accuracy of his work, and the immense amount of care-taking and tedious labor which it represents. The only regret with regard to it is that it could not have been published in full. No more important paper in its line has ever appeared in the *Transactions*. Indeed, this is a line in which far too little has been done anywhere. Geologists are not often sufficiently trained chemists to carry on such work, if they had the time; and for mining-geologists in our country the press of work in other directions is so great that they could not give the necessary time involved in this class of work, if they were so inclined. The chemist, on the other hand, is rarely enough of a geologist, or so placed, as to get sufficient field-experience to keep thoroughly in touch with the processes of nature as shown in mine-workings. By an organization like the U. S. Geological Survey, where the chemist and the geologist might work in harmony for a common purpose, it would seem that investiga-

tions into terrestrial chemistry might best be carried on; and 15 years ago, in connection with Mr. Hillebrand, one of the most thorough inorganic chemists of the day, I had planned such a line of experimental work, which I hoped might be continued as part of the regular chemical work of the Survey. But the powers that were willed it otherwise. My colleague, Mr. Becker, has made some important researches in this line, especially with regard to the natural solvents of gold, which do not appear to have come under Mr. Don's notice. Such work is necessarily very slow, and Mr. Don's paper, as he tells us, covers the results of seven years' labor.

I do not propose to discuss Mr. Don's paper from a chemical point of view, but only to consider the deductions that may be made from it from the geological side; and I do this with some hesitation, because, not being able to read his statements in detail, I may not infer correctly what his actual conclusions were. I must say, however, that he seems to be most broad-minded in this respect, and his work presents a pleasing contrast to parts of the great paper of the lamented Posepny, where the effects of the latter's recent contest with Sandberger seemed to make him look at Nature through *ascensionistically* colored glasses.

Dr. Don's first and most important conclusion from his tests is that gold does not occur in the rocks of the regions investigated by him as an original constituent of the bisilicates, and that where it is found in these rocks it is associated with sulphides, mainly of iron. His inference seems to be that it cannot be original in the rock, because pyrite is necessarily a secondary constituent, that is, one introduced after the rock consolidated. Now, my work for the past ten years has been bringing me more and more to doubt the adequacy of the bisilicates of eruptive rocks as a source of the metals for our ore-deposits, and, especially in the case of gold, to look to the pyrite, if not as a source, as the visible accompaniment. Where there is no pyrite in the neighboring eruptive rocks, I have not found that the veins are usually rich. But I have not, therefore, abandoned my belief that eruptive rocks, similar to those we see at the surface, are the source of supply from which the great majority of our ore-deposits have been concentrated. Pyrite is not necessarily a secondary constituent in such rocks,

as seems to be tacitly assumed by many. On the contrary, most petrographers admit the existence of primary pyrite, though they do not generally appreciate its importance in the study of ore-deposits. Lindgren has lately discussed primary pyrites as a product of magmatic consolidation in the gold-bearing rocks[33] of California. I cannot even feel absolutely sure, in spite of the apparent conclusiveness of Mr. Don's investigations for his regions, that the bisilicates of our Rocky Mountain eruptives may not contain some of the metals, but must wait until similarly exhaustive tests have been carried on here. Lead and cobalt have been found by Mr. Hillebrand in the bisilicates of some of the eruptive rocks of the Ten-Mile district, and lead and silver similarly by Mr. Eakins in the bisilicates of granite at Silver Cliff, Colo.

It seems important to note that the lateral-secretion theory which Mr. Don's tests seem to disprove is not the one that has been generally advocated in the United States; for I fancy few American geologists believe in the narrower view advocated by Sandberger, that the metals are derived necessarily from the immediately adjacent country- or wall-rock. Dr. Don says that he believes the gold of New Zealand is derived from rocks deeper than any now exposed at the surface there, but adds that he "is not concerned with the question whether this source is the vague barysphere, with its somewhat apocryphal contents of heavy metals." While, therefore, no longer a believer in Sandberger, he is apparently not willing to subscribe to the extreme views of Posepny. It has been the fashion for some time to decry Sandberger; but I think his work has been of the utmost value to the study of ore-deposits, even if his ultimate conclusions are not admitted; for he aroused us from the unthinking belief that the metals necessarily came from unknown depths, which it was fruitless to speculate about or to try to investigate. He started in movement the pendulum of thought, which had so long been stationary at that point; for a while it swung on his side, then back again to the ascensionist side. Now, with some geologists, it has taken a very strong impetus in the direction of the long-ago abandoned sublimation theory, or something very like it. The Swedish geolo-

[33] Gold Quartz Veins of Nevada City and Grass Valley, by W. Lindgren, *Seventeenth Annual Report, U. S. Geological Survey*, Part II., p. 94 (1895–96).

gists represented by Vogt, a disciple of the great petrographer Brögger, consider certain workable masses of iron and other ores as segregations from the still molten mass, or direct products of magmatic differentiation. Other minerals occurring in pegmatite veins, and some metallic oxides, like tin, for instance, they consider to have been deposited in the last stages of consolidation of a molten magma by a mixed process, which they call pneumatolysis, and which brings in the agency of water expelled during cooling from the igneous magma. This comes back to the old French theory of aqueo-igneous fusion in the presence of certain substances, such as fluorine, boron, chlorine, etc., which were called *agents minéralisateurs;* but it is less purely theoretical, in that it is founded on certain facts of observation in nature.

Vogt is at present preparing a new book on ore-deposits, in which he will doubtless extend very widely the scope of his pneumatolytic processes. But the applicability of either the French or the Swedish theory must be limited by a very simple geological condition, which is—whether the fissures in which ore-deposition has taken place could have been formed during the final consolidation of the eruptive magma. In most of the important ore-deposits which I have had opportunities of studying, the fissures or fractures which have served as ore-channels were the result of earth-movements that took place long after the entire consolidation of the eruptive magmas. In some cases, even, there is evidence of several such movements before the ore-deposition. My belief, as I have had occasion to state already, is that, by reason of some process which, for want of a better name, we may call magmatic differentiation, certain portions of an eruptive mass are richer in metals than the average; and that from such portions circulating solutions have abstracted these diffused metals and deposited them in a more concentrated form in favorable situations in rocks in the vicinity. The original bringing up of the metals from the bathysphere was, however, accomplished by the eruptive magma before consolidation. Present ore-deposits are in this sense the result of a secondary concentration at only moderate depths.

Dr. Don's investigation of the processes going on, or that may go on, in the vadose region affords interesting and useful data. He first assumes that deposits are generally richer in the pre-

cious metals above than below the water-line—a perfectly justifiable assumption, in my opinion—and then presents alternative explanations, one based on the ascension, the other on the lateral-secretion, theory; but he does not mention the most obvious explanation of this fact, namely, that the baser metals, which are usually in far greater amount than the precious metals, form by oxidation more readily soluble compounds, and are therefore to a much larger extent removed in the vadose or oxidizing region, while the precious metals are for the most part either not dissolved or are re-precipitated. Hence, the specific gravity of the whole mass of vein-material is decreased in the vadose region; and a given bulk, though it may have absolutely no more of the precious metal in it than before oxidation, contains a relatively higher percentage, by weight, of the precious metals. There may also be in places an actual enrichment, due to the ready precipitability of the precious metals. I have myself seen cases where, in a zone immediately above the water-line, the ore-body was not only very much richer than in the unoxidized portion below, but also richer than the average of the oxidized ore above, showing that the precious metal had been in a measure leached down and re-precipitated. Dr. Don himself shows various ways in which gold might be dissolved in the vadose region and re-precipitated lower down; he also thinks it may have been carried down mechanically; the result of his investigations of mine-waters being that, where they are found to contain gold, it is usually in mechanical suspension rather than in solution.

One of the most interesting parts of Dr. Don's investigations is that relating to the gold-content of sea-water, in which he has not contented himself with the vague statement that the metal does occur, but has made a quantitative estimate of its amount, which must be translated into the metric system in order to become intelligible to any but English chemists. The average content as determined by him is 0.0071 grain to the ton, which means, if I have calculated correctly, something like twelve million dollars' worth to the cubic mile—a large sum, if it could be gotten out. But Dr. Don has shown by a pretty exhaustive series of experiments that there is no probability that any natural precipitant would throw down any measurable portion of it.

GEORGE F. BECKER, Washington, D. C.: Dr. Don's paper is an extremely important contribution to mining-geology, and worth the vast amount of labor which it has manifestly cost. I trust that the paper in the *Transactions* will prove to be only a preliminary abstract, and that the entire *mémoir* will soon appear.

The greater part of the conclusions which Dr. Don reaches are quite in line with those to which Mr. Lindgren and I have been led by studies of the gold-deposits in this country.[34] I have been greatly impressed of late years with the character of the auriferous wall-rocks of gold-quartz veins. It seems to be true in most cases, for deep mines, that the gold in the walls is contained in the sulphurets; that it is of smaller fineness than the vein-gold; that the sulphurets are pyrites; and that gold and sulphurets diminish rapidly in quantity as the distance from the vein increases. Sometimes the wall-rock pyrite is almost barren. There appear to me to be two sorts of wall-pyrite. One seems to be the result of the action, on ferro-magnesian silicates, of the sulphides of hydrogen or of the alkalies, as I pointed out in treating of the Comstock lode. This variety is sometimes, and I suspect usually, almost worthless. There are other impregnations of pyrite which seem to me to have permeated from the vein-fissures, in solution, as double sulphides of the alkalies and iron. I have studied such solutions in a *mémoir* on quicksilver-deposits, and shown that solutions of alkaline carbonates, partly charged with hydrogen sulphide, will take up notable quantities of many sulphurets, and also of gold. Dr. Don has, I think, overlooked this investigation. Mr. Dölter has since succeeded, where I failed, in dissolving lead and silver sulphides in a similar menstruum.

Wall-rocks appear to be much more permeable by solutions of some substances than by those of others. Native gold, quartz, and all the sulphurets excepting pyrite, are for the most part retained in the veins, while carbonates seem to penetrate freely into the wall-rock. This indicates an osmotic separation of the metal-bearing solution, as I pointed out years ago.

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[34] Parts of these studies have been printed in the *Fourteenth to Eighteenth Annual Reports, U. S. Geological Survey* (1892–96).

That some undecomposed rocks (granite, andesite) contain free gold in clearly-visible particles appears to be quite certain. There is also strong evidence for the strange hypothesis that some sulphurets in massive rocks are original constituents. I entertain no doubt that some eruptive rocks associated with veins are truly metalliferous. Nevertheless, the possibility presents itself that in such cases vein and rock each derived its metallic contents from a common source, miles beneath the surface. Such a hypothesis is not without difficulties of its own, but accords better with the osmotic phenomena than the theory of derivation from wall-rock.

Dr. Don's remarks on secondary re-crystallization are interesting. That sulphurets are regenerated is certain. The question of the re-crystallization of gold needs more research.

ARTHUR WINSLOW, Kansas City, Mo.: Dr. Don's work, even as presented in the abridged form of his Institute paper, is a notable example of painstaking, conscientious research, for which the author deserves great credit. The field and literary work alone must have been very great; but, in addition, the investigation involved many special experiments on a large scale, and the testing and assaying of over 400 bulky samples, with more than 100 other assays and analyses, which, to any one familiar with such tasks, seems a stupendous labor. The results are especially of quantitative value, furnishing many exact facts and definite data which will control speculation, and upon which theories can be built up. Therefore, in whatever estimation one may hold Dr. Don's methods and results, or however one may differ in the conclusions to be drawn, all, I think, will agree in admiring the courage and entire disregard for labor which prompted and sustained his inquiries.

The investigation is, first and principally, one to determine whether the ores of certain auriferous lodes of New Zealand, Victoria, and Queensland were formed by lateral secretion or by ascension. Secondarily and incidentally, it is a valuable contribution to the general subject of the genesis of ore-deposits.

The work is of special interest when considered in connection with the hypothesis advanced by T. A. Rickard[35] for the origin of the ores of the Bendigo reefs of Australia. Indeed,

[35] *Trans.*, xxii., 289 (1893).

it would appear as if Mr. Don must have had this hypothesis immediately in mind in planning his work, so directly does he meet the questions which arise in reading Mr. Rickard's paper. Passing by his experiments and conclusions as to the precipitation of gold in marine sediments, and also allied inquiries of somewhat negative value, the results of most positive and emphasized importance are his analyses of the country-rocks for the detection of gold. These are principally interesting in the uniformity with which they show that the metal was not detected, or was found to be present only in very minute quantities in the normal country-rock; also that, where its presence was detected, it was associated with sulphides, and that both the quantity of the sulphides and the richness in gold increased as the lode or other form of deposit was approached.

The question which arises, and which to me seems of great significance, is as to the sufficiency of the evidence. Dr. Don's assay-results marked "Nil" as to gold-content must be considered as relative. They mean simply that no gold was detected by the method he used. It is probable that gold and other metals are generally diffused through the rocks of the earth's crust, and are represented normally by amounts proportional to their abundance and the solubilities of their naturally-formed compounds. The researches of Forschhammer, Dieulafait, Bischof, Sandberger, Malaguti, and others, referred to in my report on the lead- and zinc-deposits of Missouri, [36] show the frequent diffusion of copper, lead, and zinc in rocks, minerals, and waters. Mr. Robertson's analyses of crystalline and clastic rocks of Missouri, in connection with the same report, [37] sustain this belief. Proof that such diffusion is general would seem purely a question of the amount of rock used and of the refinement of method. The refinement of Dr. Don's methods may be inferred from the fact that 0.1 grain per ton is the lowest result given in figures. There is nothing between this and the "Nil" results. Gold to the amount of more than 0.1 grain he shows to be frequently present in the country-rock, remote from lodes, and even amounts of over 1 grain were found. On the assumption that the gold has been derived from these rocks, such gold now found to be present must

[36] *Reports Missouri Geological Survey*, vol. vi., p. 30 *et seq.* (1894).

[37] *Reports Missouri Geological Survey*, vol. vii., p. 479 *et seq.* (1894.)

be a residuum after the process of leaching. The question arises, what gold-content is required in a country-rock that it may be regarded as a source of the ores in the veins traversing it. Assuming 0.1 grain to the ton, it would take just 4,800 tons of rock to supply the gold for 1 ton of 1-oz. ore, if all the gold were removed from the country-rock into the veins. On this basis 1 cu. mile of rock would supply 2,300,000 tons of such ore. Mr. Rickard's hypothesis, which ascribes the gold to sea-water retained in the sediments, would hardly call for a greater original concentration, seeing that he allows only $\frac{1}{13}$ grain per ton to the sea-water of the present day.

The conception of lateral secretion as a process whereby the contents of the ore-body simple trickle in from the sides or walls can, of course, not be sustained, even though the name may seem to justify it. To harmonize with the ideas now more generally held, the flow and transmission of solutions must have been in devious directions, according to hydrostatic and thermal conditions, and according to the structure of the rocks. The solutions would naturally follow fissures, and flow into open spaces, either in ascending or descending currents. They would at the same time penetrate the wall-rocks of such openings, and when they contained gold these wall-rocks would be enriched. Thus, an increase of the mineralization, or of the gold-content, as the vein is approached, is not incompatible with the large conception of lateral secretion.

It is true that such an expansion of the original idea of lateral secretion appears to rob it of its distinctive features, so that it seems in fact to embrace the rival process of ascension, and to leave no room for the separate existence of the latter. This is not, however, the case. The essential idea of the ascension theory is that metals and other constituents of lodes are derived from a deep-seated source of supply—a sort of treasure-house of nature—whence they were transported for the use of man by the agency of ascending solutions or vapors which followed the paths of profound fissures. The opposed idea of lateral secretion, as developed, if not precisely so expressed in recent writings, is that these constituents of lodes are distributed and diffused in greater or less quantities throughout the rocks of the earth's crust—in such rocks as are or have been exposed at the surface—that they have been

gathered from these rocks and concentrated in ore-deposits by the action of percolating waters of various compositions, assisted by chemical, hydrostatic, thermal, and structural conditions, such as are brought about by sedimentation, by earth-movements, by injection of volcanic rocks, etc. In cases of the more abundant metals, such as iron and manganese, this process is plainly recognized, and the requisite conditions are commonly presented. In the case of less common metals, such as copper, lead, and zinc, the process is not so simple or so generally to be observed. In the case of the precious metals, which are rare and difficult of solution and transportation, more powerful factors and special or stronger reagents, such as highly-heated solutions, seem necessary to produce the result. Thus, according to the lateral-secretion theory, our own home country-rocks are our treasure-houses, and we are not dependent upon the foreign depths of the earth for our metals. Such may be in some cases the source of supply, but the aggressive secretionist is disposed to throw the burden of the proof upon the ascensionist, and to maintain that his rule is the more satisfactorily proved by the removal of successive supposed exceptions.

W. P. Blake, Tucson, Arizona: As appropriate to the discussion on the origin of quartz-lodes and the deposition of gold, I desire to direct attention to the very general association in California, especially in the Jura-Trias and Carboniferous slates, of gold with slates containing a large amount of carbonaceous matter. This association is particularly noticeable in the Princeton mine, on the Mariposas estate; in the Keystone mine, Amador county; in the Plumas mine, and in many other mines in the main gold-belt of the State. It has been noted also by Ross E. Browne, who, in a recent article, gives three cross-sections showing the mother-lode traversing soft black slate. He describes the lode as a "continuous series of parallel quartz veins, following more or less persistently a narrow belt of soft black slate." [38]

At the Arizona School of Mines a sample of coal has been received from Wyoming, which is said to contain gold. Preliminary assays, made with great care, show an appreciable

[38] *Mining and Scientific Press*, vol. lxxvi., No. 5, p. 105 (Jan. 29, 1898).

amount of the metal; but further investigation of the source of the coal and assays upon other samples are desirable before attaching special value to this form of association of gold and carbon.

(*Trans.*, xxviii., 799.)

DR. DON: I have to express my grateful thanks to Messrs. Le Conte, Emmons, Becker, and Winslow, for their very kind remarks, presented at the Atlantic City meeting, on my paper. An investigator works practically alone and under many discouragements, at this end of the world; and nothing has encouraged me so much in my research as to find my work appreciated by men whose wide knowledge of the subject and whose eminent services to science entitle their opinions to my deepest respect.

Professor Le Conte's last sentence gives me an opportunity to express the hope that chemical analysis may in future be more generally used as an aid to observation. If any degree of finality is ever to be reached with regard to this most puzzling question, such finality will only be attained by the combination of the experimental work of the chemist with the skilled observation of the mining-geologist.

Mr. Emmons, in his highly-valued criticism, says:

"Dr. Don's first and most important conclusion from his tests is that gold does not occur in the rocks of the regions investigated by him as an original constituent of the bisilicates, and that where it is found in these rocks it is associated with sulphides, mainly of iron. His inference seems to be that it cannot be original in the rock, because pyrite is necessarily a secondary constituent, that is, one introduced after the rock consolidated.'

I confess that I had not in my mind as clearly as I could wish the fact that in the case of crystalline eruptive and plutonic rocks the pyrite and other sulphides may be as much a primary constituent of the rocks as the bisilicates.

This distinction between primary and secondary sulphides need not, however, be observed in the great majority of the country-rocks examined by me. These country-rocks may be roughly divided into four classes:

a. Those that are unmistakable sediments, more or less altered. These form the great majority of the samples analyzed; and in these cases, all sulphides must be "secondary."

b. Dike-rocks from the Upper and Lower Silurian of Vic-

toria. None of these rocks could be obtained in the unaltered state; but those that were least altered contained no sulphides.

c. The remarks under *b* apply also to the andesites of the Thames gold-field, and the tonalite of the Charters Towers field of Queensland.

d. In the case of the gneissoid rocks of the Manipori formation of New Zealand, and the granite that probably underlies the sedimentaries of Victoria, the sulphides found in some samples may have been primary.

Mr. Emmons says:

"It seems important to note that the lateral-secretion theory which Dr. Don's tests seem to disprove is not the one that has been generally advocated in the United States; for I fancy few American geologists believe in the narrower view advocated by Sandberger, that the metals are derived necessarily from the immediately adjacent country- or wall-rock."

The introduction to Chapter V. (omitted in the condensed form of my paper) included a discussion of this point, and showed that the analysis of underlying granites and other crystalline rocks had been undertaken with a view to testing this later extension of the lateral-secretion theory. By reference to my paper [p. 162, this volume], it will be seen that the crystalline rocks were chosen because they afforded an opportunity for testing, not the actual country-rock bounding the lodes, but the crystalline rock-mass that probably underlies many of the rocks in which our lodes occur.

The majority of the results noted in Table I., *A*, *B*, and *C* (Table XVIII. of original paper), come under this heading. Owing to the great labor involved in isolating some of the crystalline constituents of such rocks, the number of these analyses is comparatively small; but so far as these results are conclusive, they point to a source for the gold below even the crystalline rocks that may be assumed to underlie our gold-bearing sedimentaries.

I have to thank Mr. Emmons for his criticism pointing out a weakness in my statement of the two alternatives on p. 172 of my paper. The second alternative should certainly have been extended in the direction suggested by him. On page 182, however, the action of the oxidizing vadose waters, in enriching vein-gold by dissolving out part of the silver, is taken into account.

Mr. Becker draws a clear distinction between the two kinds of pyrite associated with country-rock. This distinction seems to me to be of very great interest, and of the first importance.

Granted this distinction, and the selective osmotic action exercised by the wall-rock, a new light is thrown on many of the results obtained in my analyses. The apparently abnormal results obtained in some cases—more particularly in the Thames andesites and the country bounding the Reefton lodes—become much clearer in the light of Mr. Becker's remarks.

Mr. Becker refers also to the presence of visible particles of gold in undecomposed crystalline and eruptive rocks. Such instances are by no means rare; but is it not possible that the samples in which these occurrences are noticed may have been taken from the vicinity of lodes, so that the gold found may have been an impregnation from the lode itself? An interesting example of such an occurrence lately came under my notice. In a sample of syenitic rock taken from the vicinity of a copper-lode in Dusky sound, on the west coast of Otago, minute specks of metallic copper were observed, apparently forming a constituent of the hornblende of the rock. In this instance there seemed to be no doubt that the copper was derived from the lode. I should be much interested if any members of the Institute could give authentic instances of the occurrence of visible particles of gold actually forming part of crystalline or eruptive rocks at long distances from lodes.

Mr. Winslow's criticism raises the whole question as to the possibility of obtaining any experimental evidence, other than that founded on observation alone, with regard to the genesis of auriferous deposits, where the amount of metal to be looked for is extremely minute. This is a difficulty that must have presented itself to any honest worker who has made a study of the subject. The question is not so much whether the methods used by any particular investigator have been sufficiently refined, as whether any possible test may be delicate enough to give reliable results.

Now, while it is quite true that the results obtained by me do not show any difference between $\frac{1}{10}$ grain to the ton of country-rock (or one part in 156,800,000) and *nil*, and while, in my opinion, it is not possible to carry the refinement much further with safety, one must not, I think, lose sight of the fact that if

the gold of any lode had been derived by segregation from the country-rock or from associated and subjacent rocks (it will be observed that lateral secretion is here indicated in its wider sense), such segregation must have been accompanied by local deposition at many points, as the auriferous solutions made their way to the lode-fissure. It is a matter of common observation that the country, even at considerable distances from lodes, is in many cases a network of miniature lodes, where deposition might reasonably be expected to take place. In collecting samples for analysis, care was taken to include many such places of possible deposition; yet the evidence obtained by me would almost justify the general statement that in solid country, where the possibility of impregnation from a lode or dike was reduced to a minimum, no trace of gold was present, even in the sulphides found. Numerous illustrations in support of this generalization are to be found in most of the tables.

No. 9.

Influence of Country-Rock on Mineral Veins.

BY WALTER HARVEY WEED,* WASHINGTON, D. C.

(Mexican Meeting, November, 1901. *Trans.*, xxxi., 634.)

AMONG the many causes of that perplexing feature of mine-exploitation, the unequal distribution of the ore, the influence of the country-rock upon the vein-contents has long been accepted as an important factor in certain districts, but the general application of the theory has not been proved. It is now possible to obtain trustworthy data with which to test the theory, and either to confirm or to overthrow this time-honored tradition. By the searching methods of modern petrography and chemistry, rock-determinations are now scientifically made, while the examination of thin sections of ores supplements field- and laboratory-study, and affords conclusive evidence of the paragenesis of the ore-minerals.

In the great mass of data regarding mineral deposits accumulated during the past century, there are some facts which stand the test as to reliability; but the greater part are not available for use in this discussion. Within the last 20 years, however, many able workers have contributed careful and accurate accounts of various ore-deposits; and it is by the facts given in such papers, and by personal experience, that I have become convinced that there is in some districts a true relation between the country-rock and the mineral contents of the veins.

My own interest in the subject arose from the observation of a number of striking instances of the variation of vein-contents with the nature of the inclosing rock. Having already recorded certain observations of this kind, I venture to present in this paper further notes, together with a few facts from the literature of the subject, which seem to prove the correctness of my view. It is apparent that if the relation holds true, though in limited districts only, it will be of great practical in-

* U. S. Geological Survey.

terest to the miner, and will confer upon the geological survey of a mining-district a new value, rendering it, in fact, an almost indispensable preliminary to the extensive working of large properties.

The influence of the inclosing rocks upon mineral veins evidently affects both the vein-structure and the vein-filling. The first effect is physical; the second is mineralogical or, primarily, chemical. The first has been but lightly touched upon, if noticed at all, by writers on mining-geology. The second has long been recognized as a fact in a few well-known examples; but, although many attempts have been made to show a relationship between certain ores and definite rock-types, the correlations have been of local value only.

I. Influence of Rocks on Vein-Structure.

It is self-evident that in most mineral deposits the rocks must have been either porous or so fractured as to permit the circulation of underground waters as a preliminary to vein-formation. It is also evident that according to the varying hardness, toughness, etc., of the rocks, the fissures found in them will vary in character, and the physical aspect of any resultant ore-deposit will be governed by the nature of the rock.

Fissure-veins, and, indeed, all forms of ore-deposits, are affected in size and shape, and probably to some extent in richness, by the character of the fissure or fracture in which the vein was formed. Experience shows that a vein often varies greatly in structural characters, such as width, uniformity, presence of splits and horses, etc., in passing, whether horizontally or vertically, from one rock into another. Thus the vein may pinch out in a very tough rock, expand in a more easily shattered material, become dissipated into a stockwork in brittle, shattered rock, or become lost entirely in a shale. In easily-soluble rocks, like limestones and dolomites, the original character of the fissure may be modified by solution, and thus the original effects of its force may be masked. This case stands in such intimate connection with the mineralogical effects due to the nature of the rock that it is best considered in the second part of this paper. The irregular deposits formed in limestones show the influence of the inclosing rock on the form of the deposit to an even more marked degree than fissure-veins.

The fissures which, in traversing a tough rock, are clean cut, may, in passing into a more easily fractured rock, or one netted by fine jointing, produce a mass of shattered material in which the mineral is so disseminated in minute and numerous fissures that the entire mass must be extracted. Often the vein, solid and continuous in one rock, splits up, forming horses or droppers, or, if very extensive, becomes a zone traversed by many small parallel threads and stringers, too small to be worked. This is discussed by Professor Beck, in his recent book,[1] from which Fig. 1 is taken.

In the Guadalupe mine, Chihuahua, Mexico, a vein, carrying a solid ore from 10 to 40 ft. wide, changes eastward into many small branches, too small to be worked, though the richness of the ore in them may be unchanged.

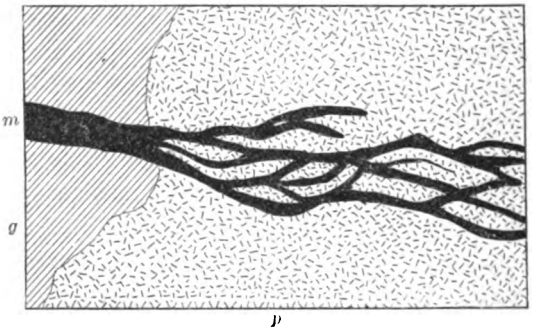

FIG. 1.—SCATTERING OF THE GOTTLOB VEIN IN QUARTZ-PORPHYRY, IN THE DAVID SHAFT, NEAR FREIBERG, SAXONY. *g*, GRAY GNEISS; *p*, QUARTZ-PORPHYRY; *m*, VEIN.

Where veins traverse foliated rocks, such as gneisses and schists, the original fissures may have been due to a very slight movement along the plane of schistosity, and the result may be linked veins, composed of numerous connected lenses, such as are commonly found in the Piedmont area of the Carolinas. If the movement is distributed over several folia the vein is not a simple one, but consists of a series of lenticular masses overlapping each other, and these may occur in a zone; so that the "vein" may be several hundred feet wide.

It is evident that, since different rocks break in different ways, the character of the fissures formed in them will depend on the country-rock. Excellent examples of the various effects

[1] *Lehre von den Erzlagerstätten*, p. 135 (1901).

due to the texture, cleavage, hardness, and other properties of the rocks, are to be seen in the silver-lead mines of Neihart, Mont., where steeply-dipping metamorphic rocks are cut by a large and very irregular intrusion of diorite, and both are cut by later intrusions of rhyolite-porphyry. Well-defined fissure-veins cross all these rocks. The metamorphic rocks consist of alternating bands of feldspathic gneiss with softer, more schistose micaceous rocks, and, more rarely, tough amphibolites. The veins cross these rocks at nearly right angles to the schistosity. The underground workings show the veins to vary somewhat in width and in the relative abundance of included rock-fragments, when they pass from one belt of feldspathic gneiss to another, and more markedly when they pass into the more schistose rocks; but the change is so abrupt

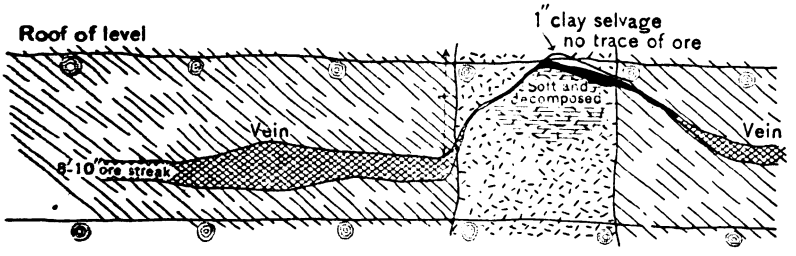

FIG. 2.—SECTION OF LEVEL, SHOWING THE FLORENCE VEIN, NEIHART, MONT., CROSSING AN AMPHIBOLITE DIKE IN METAMORPHIC SCHISTS.

where the amphibolites are encountered that the miners say the vein is faulted. In fact, the tough nature of this rock has sometimes deflected the vein, and has always, in the instances observed, narrowed it from 7 to 8 ft. in width of good ore to a foot or more of barren gangue. Fig. 2[2] is an example from Neihart, where the veins, passing from schist into Pinto diorite, a peculiar igneous rock of coarse grain and texture, are invariably narrowed, but well defined. In the rhyolite-porphyry the same fissures lose their compact character, ramifying into a network with shattered rock between, which dissipates the ore; so that, while the surface-workings are commonly rich, the ore-body does not pay in depth, owing to the large amount of waste.

[2] From the *Twentieth Annual Report, U. S. Geological Survey*, Part III., p. 421 (1900).

The same phenomenon is described by De la Beche.[3] The vein shown in Fig. 3 encounters an elvan dike, *b*, in passing from *d* to *e*, and passes up the wall of the dike, scarcely showing as a vein alongside of the dike until it crosses the dike at *c*, and continues on through the slates.

At Butte, Mont., the veins occur in a coarse-grained granitic rock (a quartz-monzonite) with intrusions of aplite-granite, and dikes of porphyry. Where the veins cross the porphyry they are narrower to a marked degree; and the same is true of the aplite. In part this is due to a more intense metasomatic replacement of the granite than of the other rocks,—a fact which will be discussed in describing the influence of the wall-rocks on the filling. It is quite evident that rock character has influenced the fissure.

The copper-veins at Virgilina, Va., which occur in metamorphic schists formed from old igneous rocks, show a structural feature common in the veins of the Southern States where

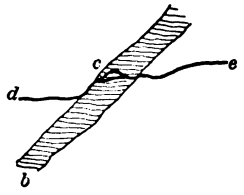

FIG. 3.—FISSURE DEFLECTED BY DIKE (DE LA BECHE).

the fissure crosses the rocks at less than 90° to the schistosity. In such cases the veins show many spurs running off for short distances from the vein along the planes of the schist. The Blue Wing mine, at the locality mentioned, shows a diabase dike cutting the schists; and where the vein crosses this rock it is narrowed and becomes a mere zone of plated rock. The spurs seen in some veins in granite are evidently the result of cross-fissures or joints, and not to be considered as a function of the rock itself.

Where the veins pass from schists into quartzite, as may be seen at Neihart, there is a marked change in their character. This is well seen at the Big Seven mine, where a well-defined vein changes to many small fissures with shattered rock between. At Frenchtown, a small settlement east of Deer Lodge, Mont., the veins in andesite-porphyry are strong and well-de-

[3] *Geological Observer*, p. 657 (1851 ed.).

fined fissures, but do not cut any other rock; hence direct comparison cannot be made. At the Porphyry Dike mine, south of Rimini, Mont., the veins are small and tight in the granite, and open out in the rhyolite into wide fissures, ill-defined, and really more like bands of shattered rock.

This variation of fissures in different rocks is especially well shown at Cripple Creek, Colo., as described by Penrose,[4] and alluded to by Van Hise.[5] In hard rock the fissures are sharp and clean-cut breaks, but in the soft rock they are ordinarily mere series of very small cracks, constituting what Van Hise calls "distributive" faults.

In slates the vein is commonly well defined, as at Copperopolis in Montana, and Parral, Mexico. In the Cœur d'Alène, in Idaho, the veins cross slates and quartzites, and present only those minor peculiarities which might be expected in passing through such rocks—in fact, there is less change than one would naturally look for.

Throughout the Appalachians the veins show a clustering of quartz lenses whose ends overlap. These have been called "linked veins" by Becker, and "compression-veins" by Stretch. That they are the result of the foliation of the schists is generally accepted. Where the lenses are parallel to the foliation there is reason to believe that they are a result of the spreading apart of the folia by movement. When the quartz lenticules lie across the vein, as they often do in the Carolinian veins, presenting the structure figured by Rickard[6] for the Victorian veins, it seems that the quartz-filled spaces result from a rending of the rock between two parallel fissures. Many of the minor peculiarities of vein-walls are due to the character of the rocks, but these are not intended to be treated here. Rickard has already described many features of vein-walls due to varying rocks.

The study of a large number of mines all over the country shows that, although no rule can be laid down for all localities, each district will present certain peculiarities. In Montana, the rhyolites are not favorable for well-defined constant veins, as the rock is too easily shattered. The granular rocks vary in

[4] Mining Geology of Cripple Creek District, *Sixteenth Annual Report, U. S. Geological Survey*, Part I., p. 144 (1894–95).

[5] "Some Principles," etc., *Trans.*, xxx., 35 (1900).

[6] *Trans.*, xxi., 686–713 (1892–93).

effect; and the more basic forms, carrying augite or hornblende, are favorable for well-defined fissures.

As it is not my intention to do more than call attention to the differences in fissuring in varying rocks, no further mention of such peculiarities will be presented here. It is evident, however, that where a single mass of rock varies in texture, as, for example, the granite core of Castle Mountain,[7] Mont., in which continuous exposures show the rock passing from granite through intermediate gradations into rhyolite-porphyry, the vein-fissures will vary with the physical characters of the rock.

II. Influence of Country-Rock on Vein-Filling.

Where a vein, passing through two different rocks, carries one set of ore- and gangue-minerals in one rock, and another set in the other, there is a strong presumption that the variation in the inclosing rock has caused the variation in the vein-materials. Similarly, if in given districts one set of vein-minerals always occurs with a certain kind of country-rock, and another set with another kind, it is probable that such association is genetic, and not accidental.

For many years there has been a widespread belief among mining-geologists and engineers that igneous rocks are an almost invariable accompaniment of productive ore-deposits of the precious metals. Whether the igneous rocks be regarded as the actual source of the metal, or as the cause of fissuring and ore-deposition by reason of dynamic disturbance, the result is genetically due to the volcanic forces. Professor Vogt has recently given us, in his able and instructive paper,[8] a *résumé* of his studies, and Professor Kemp has shown[9] both the competency of the igneous rocks themselves as a source of supply and of the intrusives as a source of energy. It is not this phase of the subject that I propose to discuss, but the time-honored question of the influence of wall-rock upon the mineral contents of the vein. Many students of ore-deposits, familiar with the common occurrence of galena-ores in limestone, and the changes in mineral character of the Cornish veins with

[7] Weed and Pirsson, Geology of the Castle Mountain Mining District, *Bulletin No.* 139, *U. S. Geological Survey* (1896).

[8] Problems in the Geology of Ore-Deposits, *Trans.*, xxxi., 125 (1901).

[9] Rôle of the Igneous Rocks, etc., *Trans.*, xxxi., 159 (1901).

change of rock, have sought to establish a relation between certain rocks and certain ores. While such a relation seems to prevail in a few districts, no general law has been established by these attempts.

Conditions Governing the Relation of Country-Rock to Vein-Contents.

In considering the relations between country-rock and vein-contents, the following premises are assumed:

1. Vein-filling may be the result (*a*) of the filling of open fissures, (*b*) of replacement, or (*c*) of both filling and replacement.

2. The ore- and gangue-minerals of all these types vary. Lindgren has divided veins filled by metasomatic replacement into 11 classes, and shows that the chemical processes involved were very different in each case. It is made certain by the study of altered wall-rocks and of mine-waters that the mineral-forming solutions have varied greatly in character. Moreover, some veins have been opened after formation, and new minerals have been introduced by later solutions.

In veins the material of which is well crustified, or is known to be the result of the filling of open fissures, a marked influence of the wall-rock on the contents of the vein would not be expected. In the majority of veins, however, there is evidence of more or less metasomatic replacement; and it is evident that the nature of the wall-rock will be an important factor in the chemical reactions of the processes of replacement. It should be remembered, however, that the evidence of many districts shows that veins of different kinds and ages may form in the same rock, and hence it is not to be expected that any general conclusions, applicable to all veins, can ever be reached.

Examples.

Butte, Mont.—In the typical silver-veins of this district the filling consists of quartz, showing well-marked "comb"-structure, with rhodonite, rhodochrosite, pyrite, zinc-blende, and silver sulphides. The structure is clearly that of the filling of open fissures. These veins occur in the normal Butte granite, a quartz-monzonite, and in the Bluebird granite, which is an aplite. There is, however, no perceptible difference in either

the character or the tenor of the ore between the veins in the aplite and those in the normal granite, or in the parts of the same vein where it cuts the two rocks. In the copper-veins, on the other hand, there is a marked difference. These are of undoubted metasomatic origin, and were formed by the replacement of the rock along fracture-planes. In the copper-area, the veins cut both the two rocks previously mentioned and also a quartz-porphyry, which I have named the Modoc porphyry. In the Butte granite, the veins are commonly rich in copper; in the Bluebird granite, they are almost equally wide and strong, but are lean, and composed chiefly of quartz, with comparatively little pyrite and copper. In the porphyry, the veins are narrow and lean. There are so many instances in which the same veins can be seen cutting all three rocks that there can be no doubt as to the correctness of these conclusions. The vein-filling consists of quartz which shows no comb-structure, with pyrite and various copper-minerals, of which chalcocite, enargite, and bornite are the most common. The walls on each side are much altered, and the less altered rocks at some distance from the veins show the ferro-magnesian silicates altered to pyrite. The relative richness of the veins in the Butte granite is believed to be due to the basic character of the rock, and its greater content of the easily-replaceable iron silicates. The rock is a quartz-monzonite, the composition of which has been carefully calculated from chemical analyses of the rock, and of the biotite and hornblende isolated from it, and from microscopic analysis of the rock as well.[10] These show it to contain 15.26 per cent. of hornblende and 4.22 of biotite. There is a little augite also. The aplite contains over 10 per cent. more silica than the rock just noted, no hornblende, and very little biotite. The Modoc porphyry also has, when fresh, a very little mica, and is as high in silica as the aplite. H. V. Winchell has called my attention to the condition shown in the diagram, Fig. 4. In the case here given as a general type, the vein is workable only in the Butte granite.

A study of thin sections of the rock adjacent to the ore shows that the hornblende is the first mineral to be altered into ore, and that the bunches of this mineral form the nucleus for a

[10] Granite Rocks of Butte, Mont. W. H. Weed, *Journal of Geology*, vol. vii., No. 8, p. 737 (Nov.-Dec., 1899).

more or less complete replacement of the entire rock. The general principles of this metasomatic replacement are those given by Lindgren.[11] It is probable that the alteration now seen in the wall-rock, with its nests of pyrite replacing the biotite and the hornblende, may present the earlier stages of the metasomatic process, and that the pyrite thus formed was not only the nucleus for a further deposition of pyrite, but that the pyrite itself was the precipitating-agent for the copper-minerals, as has been shown to be the case in the secondary enriched ores. In the aplite there is more quartz and less pyrite, and the latter mineral is noticeably poor in copper. The same general statement also holds true for the porphyry.

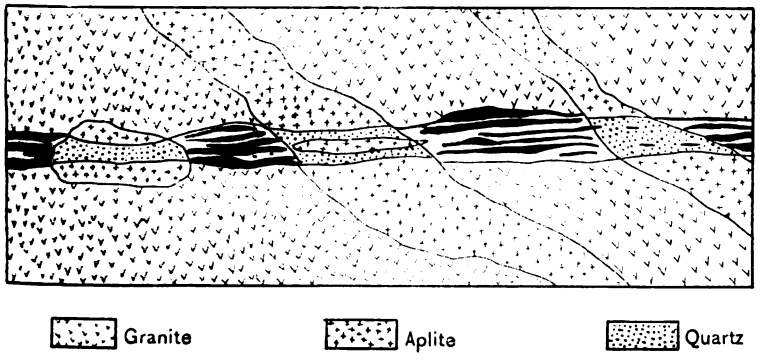

FIG. 4.—IDEAL PLAN OF CONDITIONS IN A COPPER-VEIN AT BUTTE, MONT., PASSING FROM BASIC GRANITE INTO APLITE MASSES.

The solid black represents high-grade copper-ore, when the vein is in basic granite.

The Dolcoath mine of Cornwall is perhaps the best-known example of a vein, the mineral contents of which vary with the nature of the inclosing rocks. As described by many writers, the veins carry copper-ores in slate and tin-ores in granite. Stretch[12] gives a further example of argentiferous galena with its usual associated blende and pyrite in a decomposed plagioclase porphyry, changing to auriferous arsenopyrite in the underlying granite.

Cornwall.—Fissures crossing the contact of granite or other intrusive rock with sedimentary rocks are not uncommonly productive, when the district is metalliferous. This is very marked in the Cornwall mines, where bunches of ore occur at

[11] Metasomatic Processes in Fissure-Veins, *Trans.*, xxx., 578 (1900).

[12] *Prospecting, Locating, and Valuing Mines*, p. 135 (1899).

the junction of granite and schist. De la Beche[13] mentions fissures traversing schists and passing through a dike of porphyry (elvan) some 300 ft. thick. The vein above the dike carried little ore; in the elvan, ore was abundant and rich, but became poor again in the slates beneath (Fig. 5). This occurrence of ore-bunches where fissure-veins cross such dikes has always been known to the Cornish miners. When the lodes pass into the dikes, they are often branched and split, as shown in Figs. 3 and 6 (after De la Beche); and in such cases, though the total amount and richness of ore be the same, the vein may not pay to work, on account of the large amount of waste.

Pontgibaud, France.—Here the silver-lead veins occur along fractures within granulite dikes, and on the line of contact with the gneiss country.

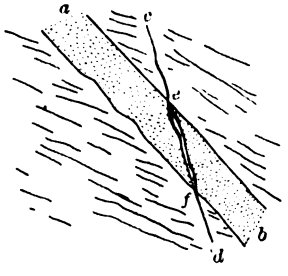

FIG. 5. — SECTION ACROSS WHEAL ALFRED GWINEAR, CORNWALL. RICH ORE OCCURS IN THE DIKE ONLY. (FROM DE LA BECHE.)

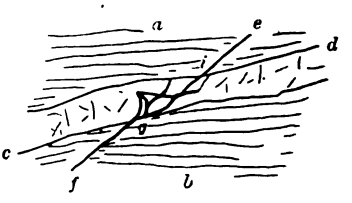

FIG. 6.—VEIN SPLIT IN TRAVERSING JOINTED "ELVAN" DIKE (DE LA BECHE).

"When the dike diminishes in size the vein decreases in width; when the vein penetrates the gneiss the ore disappears. The best ore is associated with the kaolinization of the feldspar of the granulite; when the latter becomes hard, unaltered in depth, the ore pinches out."[14]

Rico, Colo.—Rickard also mentions the veins of rich gold- and silver-ores at Newman hill, Rico, Colo., as "noticeably affected by the character of their rock-walls." There is a marked change in passing from limestone into sandstone; and generally the veins are richest in the darker-colored sedimentary rocks. The interdependence between country-rock and ore is briefly discussed by Rickard, who adopts Cotta's explanation that the physical texture and chemical composition

[13] *Geological Observer*, p. 678 (1851 ed.).

[14] T. A. Rickard, Vein Walls, *Trans.*, xxvi., 200 (1897).

of the country-rock affect the deposition of ore, and declares that it was undoubtedly the carbonaceous matter of the rock at Rico which acted as a precipitant. This example differs, therefore, from that of Pontgibaud, where feldspar has been replaced by silver-bearing galena.

Neihart, Mont.—At this locality the veins show a remarkable variation in richness, corresponding to differences in the wall-rock. Robert H. Raymond, the former manager of the Diamond R. properties, found that the veins were barren in the dark-colored gneisses, and held ore-bodies in the pink or white feldspathic gneiss. My own observations enabled me to confirm this in a general way, and also showed that in amphibolite the vein was barren as well as narrow, and that no work-

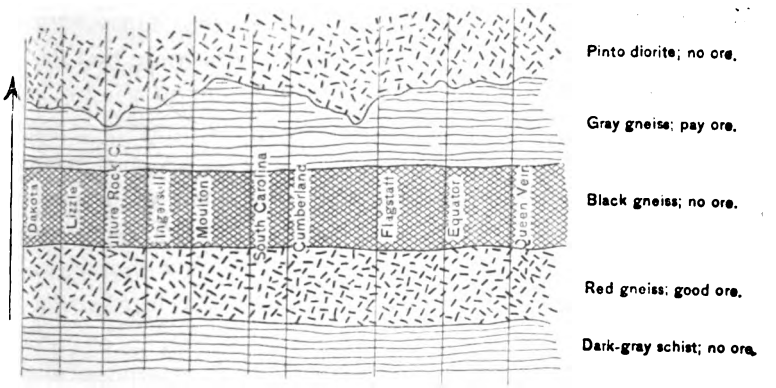

FIG. 7.—DIAGRAM (PLAN) SHOWING ROCKS TRAVERSED BY THE NEIHART VEINS, AND RELATION OF PAY-ORE TO COUNTRY-ROCK. (The veins are indicated by simple parallel lines.)

able ore-bodies had been found in the diorite. In quartzite and in the intrusive rhyolite-porphyry the veins have proved rich near the surface, but the values have gone down but a few yards. It is believed, however, that this is because of structural conditions, with secondary enrichment of a shattered zone, rather than because of a mineralogical condition due to the nature of the inclosing rock. These conditions are indicated in Fig. 7, reproduced from the report on the district.[15]

Furstenburg.—A similar example is quoted from Fournet by De la Beche.[16] The Wenzal vein at Furstenburg is nearly

[15] Geology of the Little Belt Mountains, Montana, *Twentieth Annual Report, U. S. Geological Survey*, Part III., p. 419 (1900).

[16] *Geological Observer*, p. 680 (1851 ed.).

vertical and cuts down through many beds of gneiss, about 60 ft. thick, that dip east. In the micaceous gneiss the vein is a nearly-imperceptible string of clay. In argillaceous slates it suddenly becomes from 12 to 18 in. thick, consisting of baryta, ruby-silver, large masses of antimonial silver, and argentiferous gray copper. In the hornblende-gneiss it continues, but the silver-ores are wanting and galena is the only ore. In the fourth series, of slightly micaceous beds of gneiss, the silver-ores are as abundant as in the argillaceous slates; but they gradually disappear in depth, being replaced by selenite and galena.

It will be noted that the Neihart veins present several contradictions to the rule observed in the Butte district. The ores occur in the feldspathic rocks, carrying little ferro-magnesian minerals. The basic amphibolite and the diorite are both barren. It should be noticed also, in this connection, that the ore-depositing solutions were markedly different in the two cases. In the Neihart veins the gangue is mainly a mixture of carbonates of lime, iron, and manganese. The ores are also markedly different, as they consist primarily of galena with sphalerite and pyrite, which is secondarily enriched in the upper parts of some veins. The solutions have been of such a character as to react with the feldspars rather than with the ferro-magnesian silicates.

Other Montana Localities.—In the silver-lead camp of Barker in the Little Belt mountains, near Neihart, as at the mines at Castle, Mont., and a score of other places where the ores occur in limestone, it is evident that different action has taken place. Here, as is so very commonly the case, the ore-bodies occur in limestone near the contact with igneous intrusions. The heat of the latter and the vapors of the cooling magma have altered these limestones to more or less coarse-grained marbles, if the limestones were pure, or to mixtures of garnet, epidote, and other silicates, if the limestones were impure. The latter is the case at the Trout mine and other contact ore-bodies near Philipsburg, Mont., where the Granite Mountain vein (of quite different and drier ore, without lead) occurs in the granite. In this case the gangue is largely silica; and it is probable that similar solutions circulating as a result of the heat supplied by the igneous intrusion, and, in part, at least, in fissures formed

in rocks by the intrusion, formed one set of ores in the limestone and another in the granite.

Another instance of the difference of mineral contents in the same ore-deposit in different rocks is shown by the Elkhorn mine at the town of that name, Jefferson county, Mont. This deposit is peculiar in its structural relations, being similar to the well-known saddle-reefs of Australia in that it occurs in a saddle-shaped mass along the axis of a steeply-pitching anticlinal fold. The rocks are sedimentary, of probable Cambrian age, and dip at steep angles towards the contact of a great mass of granite and other intrusive igneous rocks. The ore occurs at the contact between an altered shale and a massive crystalline limestone, and both rocks have been changed by contact-metamorphism. The bedding-plane is ore-bearing only where the general dip of the rocks is disturbed by flexures. In addition to the ore found along the contact, a number of very large ore-bodies have been found at some little distance in the dolomite, though always in the same structural position. The ore found along the altered shale-dolomite contact is essentially a "dry" quartzose milling-ore; that of the dolomite, mainly galena, with accessory sphalerite and pyrite. Both ores are connected by "pipes" and stringers, and both the field- and the microscopic evidence shows that they were formed by the same solutions and at the same time. There is no escape from the conclusion that the difference in the mineralogical character of the ores is the result of the different nature of the inclosing rock.

It would be tedious to enumerate all the familiar deposits in limestone. Those of Leadville, Colo., and Eureka, Nev., have been thoroughly studied and described. Tombstone, Ariz., presents quartzose veins filling fault-fissures, cutting slightly-tilted sedimentary rocks, with the workable ore-bodies formed by replacement of limestone along bedding-planes, and presumably by the same solutions that filled the fissures.

Derbyshire.—The Derbyshire lead-mines of England are also well-known examples of veins carrying galena in limestone, and barren when in the intercalated intrusive trap-rocks (toadstone). Fig. 8, from De la Beche, illustrates the occurrence of galena in the limestones above and below an intrusive sheet in one of the Derbyshire mines. The leader or fissure traverses the

"toadstone" as well as the lime-rock, but it is only in the limestone that galena occurs in the altered area. The channels or rakes (*g i*, *a k*, *c m*,) were fissures, through which solutions reached the pipes or ore-bunches, *p p*, the bedding-plane deposits, *f f*, and the joint-deposits, *h h*.

Contact-Deposits.

As Lindgren has remarked in discussing the formation of contact-deposits, a chemical reaction seems to take place between the substances leaving the magma and the carbonate of lime, causing the deposition of new minerals and the liberation of carbon dioxide. In the cases mentioned in this paper, the evidence shows that the veins were probably formed, not by true pneumatolytic action, but by hot circulating waters which were as truly a result of the igneous intrusion as the vapors and gases of pneumatolytic action. The escaping vapors and gases from the magma were, it is believed, taken up by circu-

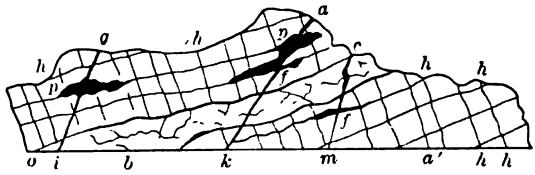

FIG. 8.—LIMESTONE BEDS OF DERBYSHIRE, WITH INTERCALATED BEDS OF IGNEOUS ROCK (TOADSTONE) TRAVERSED BY VEINS. (DE LA BECHE.)

lating waters of either deep-seated or meteoric origin, so that the "mineralizing-agents" which had taken up and formed the volatile compound of various metals, as supposed by Lindgren, passed into solution. Concerning the occurrence of this class of deposits in limestone, Mr. Emmons's description of the Greenwood ores is quite significant. He says: "The ore-bodies are cut by eruptive dikes that do not apparently disturb or exert any *metamorphic influence on the ore*, and yet are not at all mineralized themselves." At a number of localities seen by the writer, the veins, if traced into the granite or diorite, would be found to be barren of galena, and generally without value. On the other hand, at Marysville, Mont., the veins show no appreciable change in character in passing through the altered shales or hornstones into the granite. It should be noted, however, that the ores at this place are not lead-

bearing. Moreover, I am told by G. H. Robinson, the former manager of the mine, that in the earlier workings the veins showed a marked tendency to be richer in approaching the granite (or rather diorite) contact, and were poor when they passed into the granite.

Thunder Bay Silver-Veins.—H. V. Winchell tells me that the Thunder Bay district of Canada affords excellent examples of vein-variation in different rocks. The basaltic caps and sills of that region overlie Animikie slates and argillites, resting in turn upon taconites and several hundred feet of cherts. These rocks rest upon the basal quartzite overlying the Archæan complex. The silver-veins are often from 8 to 10 ft. wide in the slates, and carry native silver and argentite with small amounts of blende, galena, and pyrite, in a gangue of quartz, barite, calcite, fluorite, etc. They are wide and productive in the slates, but split up into narrow and barren seams in the overlying trap-rock, and are barren in the underlying cherts and Archæan rocks. The Rabbit, Silver Mountain, Beaver, and other mines have been noted producers.

Kemp[17] describes the Silver Islet mine as a fissure-vein carrying native silver, argentite, tetrahedrite, galena, blende, and nickel and cobalt compounds in a calcite gangue. The vein is in flags and shales of the Animikie series (Algonkian) and cuts a large trap dike (gabbro), *within which alone the vein is productive.*

Influence of Carbonaceous Matter on the Formation of Ore.

The well-known reducing action of carbon has long been an accepted explanation of the occurrence of ore-bodies in carbonaceous shales. The silver-veins of the Animikie slate are often cited as examples. The Australian veins, which carry rich gold-ores only where they cross "indicators," are a well-known instance, and the *Fahlbands* of Norway another. Rickard ascribes the Australian ore-bodies to the reducing action of the carbonaceous shales. All the descriptions show, however, that although these indicator-reefs are strata of carbonaceous shale, they are remarkable for the amount of pyrite they contain, while other shale-beds crossed by the veins are also carbonaceous, but not pyritic. In previously-published

[17] *Ore-Deposits*, 3d ed., p. 283 (1900).

papers I have called attention to the reducing action of pyrite on solutions carrying copper-salts; and believe that this mineral is the real precipitating-agent in both the Australian and Norwegian ores cited. This view, based upon field-observations and laboratory-experiments, in connection with the work of the U. S. Geological Survey, is strengthened by the experiments made under the direction of my friend, H. V. Winchell, geologist of the Anaconda Copper Co., who finds that the mine-waters of that company's properties, though strongly charged with cupric sulphate and ferric sulphate, also contain large amounts of carbonaceous matter from the old mine-timbers. It is evident that if the carbon were an active reducing-agent, it would reduce the ferric iron to the ferrous condition. On the other hand, experiments show that pyrite from the Butte veins left for several weeks in the natural mine-waters became coated with copper-glance (Cu_2S).

Dependence of Vein-Minerals on the Character of Wall-Rock, Due to Metasomatic Chemical Reactions.

The examples given show that a variation of mineral contents coincides with the change of country-rock in many places and in many kinds of veins. A study of the vein- and gangue-minerals and of the rock contiguous to the ore-bearing fissures is therefore essential to a complete understanding of the origin of ore-deposits. The rocks forming the vein-walls are commonly altered. Where no such alteration is observable, it will usually be found that the veins are the result of the filling of cavities, and are thus excluded from the category discussed in this paper. Nevertheless, some metasomatic alteration of the rock adjacent to the fissure is usually present; and it must be admitted that many veins show evidence both of the filling of open cavities and of deposition by replacement.

As already indicated, the coincident variation of mineral contents and wall-rock is due to metasomatic action, whereby there is a chemical interchange between the rock and the vein-producing solutions. The metasomatic process varies greatly because the solutions vary. Lindgren [18] has treated the subject fully, and has indicated the chemistry of the process, so that a detailed account of the reactions involved is unnecessary here.

[18] Metasomatic Processes in Fissure-Veins, *Trans.*, xxx., 578 (1900).

According to his clear demonstration, the alteration of the same kind of wall-rock shows that the vein-forming solutions have varied greatly in their chemical effect upon vein-contents, even where the veins are of metasomatic origin.

The most frequent process seems to be, in granitic rocks, a reaction between the ferro-magnesian minerals, such as augite, hornblende, biotite, etc., and the vein-forming solutions, with the formation of pyrites and other sulphides. If later reconcentration occurs, bonanzas are formed by reaction of the pyrites on later solutions. This process I have treated quite fully in a monograph now in preparation on the Butte ore-deposits.

In other cases, the feldspars are attacked, and the iron-minerals of the rock are not *replaced.* Such a case is described by R. C. Hills;[19] and Rickard ascribes the silver-lead ores of Pontgibaud, France, to the replacement of the feldspars of granulite, as already quoted.

The attempt to tabulate the relation between vein-contents and country-rock has been made by various writers, and lately by Stretch. The latter author, in his very interesting essay,[20] has given 139 occurrences, and attempted to eliminate the personal equation of the observer. It is evident, however, that existing literature is not adequate for such work. Too often the rocks are wrongly named, or receive generic terms only. The words "granite" and "porphyry" have long been used in a textural sense by mining engineers, and by many geologists unfamiliar with petrographic distinctions; and, as is well known, shales, limestones, and sandstones grade into one another. For the careful study of metasomatic replacement, which must be made to establish scientifically a relation between country-rock and vein-filling, finer distinctions must be made. The granitic rocks of some writers include gabbros, diorites, granite, and aplite, with a wide range of mineral and chemical compositions. The most that can be attempted at present is to present the known facts of occurrence in deposits about which there can be no doubt, or which have been carefully studied. The facts here set forth show the advantages of geological examination of the district about a mine, especially

[19] *Proceedings of the Colorado Scientific Society,* vol. i., p. 20.

[20] *Pocket-Book for Prospecting, Locating, and Valuing Mines* (1900).

of the area containing the vein. It is evident that it is important to ascertain the extent laterally and the probable extent vertically of the rock in which the ore occurs; and, if other rocks occur, what they are and what effect, if any, they will have on the vein-fissure and vein-filling. Such associations have long been recognized in a rough way by the miners, who say "that mineral will not live long in such a rock." The instances noted in the literature of ore-deposits are few, compared to those actually encountered in mining-operations, where the character of the vein has changed in depth. Such change is, it is true, very often due to secondary alteration, with or without reconcentration and enrichment of material, but in many cases it is probably due to change of rock.

Conclusions.

From the evidence presented the following conclusions are drawn:

1. The structural characters of vein-fissures, such as course, width, etc., vary with the nature of the country-rock.

2. The mineral contents of veins formed wholly by the filling of open fissures are not affected by the nature of the vein-walls.

3. The mineral contents of ore-deposits formed by metasomatic replacement vary with the nature of the inclosing rock.

4. As metasomatic processes vary in character with the nature of the solutions, no invariable general relation can be established between certain rock-types and rich ore-deposits.

No. 10.

Igneous Rocks and Circulating Waters as Factors in Ore-Deposition.

BY J. F. KEMP, NEW YORK, N. Y.

(New Haven Meeting, October, 1902. *Trans.*, xxxiii., 699.)

In submitting an additional contribution to the discussion on ore-deposits in the recent volumes of the *Transactions*, it is my desire to adhere closely to matters of material importance as affecting the actual processes. Judging from the discussion by Professor Van Hise, and from one or two reviews or other articles by associates of his in geological work, the impression seems to prevail that, in so far as my paper* referred to his masterly essay,† I was guilty of misconceptions regarding both the part attributed by him in it to the igneous rocks and the ubiquitous presence of the ground-water. I should regret extremely to be wanting in these particulars or to have misunderstood one for whose great services in this and other branches of geology no one has a higher esteem than myself. I have, however, in the most careful way, and with these points in mind, read his essay again, and, taking it as a whole, I cannot gain any different impression of relative magnitudes than the one first received. The importance of the igneous phenomena and the restrictive influence of the processes described by "cementation" in their effect upon the ground-water, as set forth in Professor Van Hise's "Discussion" (*Trans.*, xxxi., 292), impress me as being in very marked contrast with the same things in his first essay. If the point seems to anyone of sufficient importance, it can easily be decided by reading the originals. My paper was the result of some years of observation, reading and reflection, and was meant to be an independent contribution, controversial only in some subordinate particulars. In depicting the drama of the deposition of ores, I cannot but feel that Professor Van Hise assigned to the chorus and the scene-shifters some characters which, it seems to me, should

* "The Rôle of the Igneous Rocks in the Formation of Veins," by J. F. Kemp, *Trans.*, xxxi., 169, and *Genesis of Ore-Deposits*, p. 681.

† "Some Principles Controlling the Deposition of Ores," by C. R. Van Hise, *Trans.*, xxx., 27, and *Genesis of Ore-Deposits*, p. 282.

have been among the leading parts. This is not to imply that the chorus or the supernumeraries are unimportant or unessential members of the cast. On the contrary, no presentation could be given without them; and the earnest student of the text of dramas will quite invariably find them mentioned in the inconspicuous way appropriate to their modest station.

Still, psychology on the surface of the earth does not materially affect the production of veins in the depths; and, with this preliminary clearing of the ground, points of more consequence may be taken up. All veins and replacements, and the greater number of contact-deposits, must have been produced through the agency of underground water aided by auxiliary reagents and heat. No sensible man can doubt this. Unquestionably, moreover, where there is a continuous column of water possessing "head" and operating through sufficiently open channels, circulation will ensue. The underground water and related solvents must be derived either (A) from the emissions of eruptive rocks or (B) from meteoric sources, possibly during sedimentation. When the latter, the heat which is essential to promote circulation must come (1B) from the crushing and frictional rubbing of particles or similar dynamic causes in rocks, or from chemical reactions; (2B) from the normal increase of temperature with depth; or (3B) from igneous intrusions. (Compare "Principles, etc.," *Trans.*, xxx., 49. Much the same appears in the writer's "Ore-Deposits of the U. S. and Canada," 3d ed., pp. 26 and 27, 1901.) The discussion of these several topics will, I believe, cover the debatable points.

A. Emissions of eruptive rocks. This point has been discussed briefly in the first part of my former paper, and I am led to believe that it deserves all the importance which is there given it. A citation from the *Zeitschrift für praktische Geologie* for October, 1901, p. 383, bears on this point. The original in the "Echo" is inaccessible to me.

"The gases which are emitted by the plutonic rocks, when the latter are strongly heated, present a subject of notable interest in so far as it is necessary to believe that a part of them were enclosed in the rocks at great pressure at the time of consolidation. According to the 'Echo,' Armand Gautier has submitted to strong ignition a number of rocks which had crystallized at high temperatures and pressures. From each 100 volumes of the following varieties he obtained at

a red heat the stated volumes of gases: granite, 670; ophite, 760; porphyry, 740. Since we must believe that these rocks, while beneath the surface, were often heated to similar temperatures, which are below those prevailing at their time of consolidation, it is clear that the results possess an important bearing upon the question of the production of the volcanic gases and of those dissolved in hot-springs. If we give due weight to the expansive power which these rock-gases must develop whenever the pressure upon the heated rock in the interior of the earth permits, we see that the old theory of the production of volcanic outbreaks by the introduction of water is no longer necessary. By a still stronger ignition the volume of the emitted gases appreciably increases. At 1000 degrees (centigrade) granite affords, according to the calculation, 20 times its own volume of various gases, besides 89 times its volume of steam; that is, more than 100 times its own volume of gases and vapors. When one realizes the explosive power which this implies, one may dismiss the introduction of surface waters into the glowing reservoirs of rock from the theories of volcanic action."

I will, however, bring these matters in as important factors in the production and circulation of underground waters and the formation of ores; and, so long as their original presence in the igneous rocks is admitted, it is a matter of small moment, in this connection, whether the magmas are brought up into the zone of circulating waters by gravity, according to the views of Dutton, Gilbert and Van Hise, or by the exhaustive force of the once occluded vapors themselves, as other authorities of equal weight maintain.

The general conception also gains much support from what we know of the contact-deposits which are found on the borders of eruptive rocks and limestones. Mr. Lindgren's paper* bears on this subject. I have recently had the opportunity to study one of the largest of the Mexican cases, and it seems to corroborate the derivation of ores directly from a magma. In the course of the intrusion of a series of eruptives at San José, Tamaulipas (which will be soon described in detail by my assistant, Mr. George I. Finlay), about midway in time, there came a laccolithic mass of andesitic rock which embraced in itself huge masses of Cretaceous limestone. It has produced contact-zones of garnet-rock, with magnetite, a little specular hematite, and great quantities of pyrite and chalcopyrite. All these must be considered to be the products of contact-metamorphism, and, except in the matter of certain minor rearrangements, there is no reason to think that meteoric waters

* "The Character and Genesis of Certain Contact-Deposits," by W. Lindgren, *Trans.*, xxxi., 226, and *Genesis of Ore-Deposits*, p. 716.

have had any share in their production. The limestone, which is quite pure, yielding over 50 per cent. of CaO, as I understand from the smelter-records, has been changed to garnet with something like 15 per cent. of CaO. There must have, therefore, been an enormous emission of SiO_2 and other substances from the magma. Certainly a million tons would be a small estimate of the garnet-rock actually in sight within an area of 2 or 3 square miles. Let us suppose, now, that a magma charged with these materials were intruded in some other rock than limestone, such as sandstone or granite, or some intractable material. The same emission of silica, of sulphur and of metallic bases would certainly take place; but not being able to react on the walls, and not being held by them next to the eruptive, they must migrate upward through fissures. It is, moreover, inconceivable that they should be emitted otherwise than in association with much more steam or potential water than their own mass, and one must believe that they would be yielded under such pressure and with such a *vis a tergo* that they would not need any other motive power to drive them upward. In higher levels, metallic veins with prevailing quartz-filling and all the common varieties of ore-deposits would result. They might mingle with meteoric waters to a certain degree, and beyond question would; but the latter would play no necessary or essential part in the process. The original deposits might be later rearranged by the circulations of meteoric waters, and I realize perfectly, from the recent observations of Messrs. Emmons, Weed, Van Hise, De Launay and others, that there is every reason to believe that they would be; but it is not necessary to assume such arrangements in order to yield an ore-body.

Mr. Lindgren's paper on contact-deposits refers to a number of others similar to this Mexican one, which, in fact, he also cites, quoting a very brief reference to it by Ordoñez; but there are many more. There is a very large one, for example, at San Pedro, N. M., a detailed description of which has been given by two members of the Institute, Messrs. Yung and McCaffery.* I have had the privilege of going over the ground with them the past summer. Notes upon still ad-

* "The Ore-Deposits of the San Pedro District, New Mexico," *Trans.*, xxxiii., 350.

ditional cases have been received from other old students and friends. The very valuable contributions, moreover, of Messrs. Weed and Barrell* upon the Elkhorn district, Montana, have served to show the important preparatory work of contact-metamorphism in producing porous rock wherein ores may later be deposited. Mr. Weed has shown that the Cananea mines, Sonora, Mexico, are of this type; and informally, from Dr. W. L. Austin, the writer has learned of many additional cases.

The recent exhibitions of vulcanism in the West Indies must bring the force of these statements home to any one who reflects upon them. That the sea or any form of meteoric water could have contributed more than a small portion, which was caught up as the explosive vapors progressed toward the surface, seems to me contrary to sound principles in physics. In fact, I cannot resist the conviction that in the study of vulcanism and its effects lies the promising field of investigation which will throw additional light upon the production at least of the first deposits,† which may afterwards experience enrichment in their upper portions from the action of meteoric waters.

The pegmatites and at least their limiting quartz-veins were certainly produced in very much the way just outlined. They are very widespread. Mr. Lindgren mentions the general experience that they are barren of ores,‡ and I have likewise remarked this feature;§ but Dr. O. A. Derby has recently contributed to the Institute some notes on Brazilian gold-veins in which he describes a very extensive series of rather richly productive veins of this character.‖

If, now, we add to the above considerations the further one of the almost constant association of eruptive rocks with veins,

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* "Geology and Ore-Deposits of the Elkhorn Mining District, Jefferson Co., Mont.," by W. H. Weed; "Petrography," by Joseph Barrell, 22*d Ann. Rept. U. S. Geol. Survey*, Part II., p. 399. "Physical Effects of Contact-Metamorphism," by Joseph Barrell, *Am. Jour. Sci.*, April, 1902, p. 279.

† A very suggestive essay bearing on this point is that of L. De Launay, "Contribution a l'Étude des Gîtes Métallifères," *Annales des Mines*, August, 1897, p. 119.

‡ "Character and Genesis of Certain Contact-Deposits," *Trans.*, xxxi., 243, and *Genesis of Ore-Deposits*, p. 732.

§ "Rôle of the Igneous Rocks, etc.," *Trans.*, xxxi., 183, and *Genesis of Ore-Deposits*, p. 694.

‖ "Notes on Brazilian Gold-Ores," *Trans.*, xxxiii., 282.

and the usually very restricted occurrence of the latter, it seems to me that, areally considered, we have adequate reason to attribute to the former, and especially when there is no positive contradictory evidence, very great importance in vein-production. It is reasonable, efficient, demonstrated in important cases, and in no respect more speculative than the inferred deep circulations of descending meteoric water. I do not state this controversially, but as a claim for its recognition.

When ore-formation is referred to pneumatolytic or fumarolic action, I understand that practically these processes are meant. Under these names, or with a general statement similar to the one given above, the processes have been often appealed to.* Nevertheless, such unquestioning faith has generally been felt in meteoric waters that the possibilities of this general cause have received comparatively little attention.

B. Regarding the general question of the descent of meteoric waters into the earth, there developed in our two papers considerable difference of opinion between Professor Van Hise and myself. I am entirely frank to admit that I gained from his "Principles" the idea that he believed the meteoric waters to be everywhere descending, migrating laterally through the smaller waterways, and, although guided by relatively impervious beds, pitching anticlines, etc., to be then returning to the surface by the trunk-channels. This is certainly the conception of the ground-water hitherto held by the lateral-secretionists. I have again and repeatedly read the parts of the essay bearing on this subject, and I cannot blame myself for reaching this conclusion. I therefore laid stress, and with entire justification, upon the dryness of deep mines, in order to delimit or disprove it. Professor Van Hise's rejoinder† to my arguments strikes me as a great restriction upon what I believed to be his conception, and, were it not for his statement to the contrary, I should conclude that his attitude had been much modified. The latter expression makes it less difficult for us to attain

* For instance, by von Richthofen for the Comstock lode; by J. S. Curtis for Eureka, Nev., Monograph VII., *U. S. Geol. Survey*, p. 89; and by Arnold Hague, Monograph XX., 294; by J. E. Spurr for Mercur, Utah, 16*th Annual Report*, *U. S. Geol. Survey*, Part II., p. 402; and by the last named, again, in the 18*th Annual Report*, Part III., pp. 297 to 316.

† *Trans.*, xxxi., 300 and 301.

approximate agreement. I am quite free to admit that it is possible that the advance of "cementation" may plug up cavities so as seriously to impede circulation. This would be especially effective in the larger channels where the main ore-bodies such as we mine are precipitated. If, then, a mine went down on a filled and plugged vein, water might reasonably diminish and disappear with depth. It is less easy to believe that the same results would take place in the smaller and tributary conduits which feed downward and into the larger up-takes, because they must be kept open in order to bring in material wherewith to plug the latter. If, then, deep shafts in a district of heavy rainfall like the copper region of Keweenaw Point, before reaching the ore-body, cut nearly a mile of strongly inclined lava sheets, a hundred or more in number, and many of them amygdaloidal, without finding water below a comparatively shallow depth, it proves that rocks are ordinarily much more impervious than has been supposed in most discussions in the past regarding the descent of meteoric waters. I learn from friends who have been in the Transvaal gold regions that the deep shafts there, which, as we all know, are sunk through one flank of a syncline of sedimentary strata, likewise find dry ground at a depth of about 250 ft. Aside from any bearing upon Professor Van Hise's essay, I think it is important to emphasize these points. I am frank to admit that I did not fully appreciate the force of this observation myself until I came to prepare the paper on the "Rôle of the Igneous Rocks;"* and yet, despite the force of Professor Van Hise's reply, I cannot say that I believe that the damaging effects of experience in deep and dry mines upon our older conceptions of the descent of the meteoric waters (conceptions which I have held in common with geologists in general) have been satisfactorily met by Professor Van Hise in advancing the idea of the zone of cementation. The dryness of deep mines destroys for a large part of the earth the very foundations of Professor Van Hise's main contention; and in meeting this objection with the conception of the zone of cementation he may well be, as it seems to me, merely opposing a damaging ma-

* *Trans.*, xxxi., 169, and *Genesis of Ore-Deposits*, p. 681.

terial fact with a largely subjective conception. I am led rather to have the more confidence in the intrusive rocks and their emissions. In this connection it may be of interest to remark that in a paper in vol. vi. of the *Transactions*, pp. 544 and 545, 1877, Dr. Raymond has outlined briefly both sides of this discussion.

Let us, however, admit that, after periods of upheaval and special fracturing, the meteoric waters descend with all the facility and in all the abundance required by the conception formulated by Professor Van Hise. According to this, as I understand it, the cause of their return to the surface from the depths, which, as the extreme, are about 10,000 meters, is the "head," or the amount by which the pressure at the base of the descending columns exceeds that at the base of the corresponding ascending columns. The head is chiefly due to the greater length of the former column, because it is fed from entrance-points which are above the points of emergence of the returning waters; but the head is reinforced by the expansion produced in the ascending and hotter column because of increments of heat absorbed at a greater or less depth within the earth. The motive power is, however, the head in all cases; that is, it is gravity. I do not for a moment question the force or attractiveness of this conception, nor the able way in which it has been presented by Professor Van Hise, even though I have not the same faith in its efficiency which he evidently feels.

It is clear that if "head" is at all active, there must be a continuous and unbroken column of water from the surface, or from very near the surface, to the ultimate depths reached by the meteoric waters, and back again to their point of emergence. This pressure or head must be transmitted through all the cavities, small and large, capillary, subcapillary and supracapillary, which the waters traverse. It seems to me to demand, where it operates, practical saturation of the crust of the earth with water,—a condition which experience in deep mines proves to exist, so far as I know, in no mining-region to-day, except, perhaps, in one or two of obvious expiring vulcanism. Despite the conception of the zone of cementation, earlier referred to, I am influenced by this experience.

In discussing the transmission of pressure through cavities of capillary size by the descending waters, I regret that I did do Professor Van Hise an unintentional injustice, as he remarks in his closing discussion, in that I confused the passage of the descending waters under pressure, through capillary tubes, with capillarity or capillary attraction. The interposition of the latter would destroy "head," but the interposition of the former would only greatly reduce it because of friction,—a point emphasized by Professor Van Hise.

There is no question that, if meteoric waters enter a fractured and open-textured portion of the earth, descend, migrate laterally in unbroken course, and meet uprising fissures which reach the surface at lower points than the place of entry, they must emerge and establish a circulation. The points open to argument are, first, the extent and relative amounts by which the different sources of internal heat may aid them or substitute a source of energy even greater than "head" or gravity; second, whether they are, on the whole, as efficient causes of vein-formation as intruded rocks and their emissions; and, third, whether the general geological relations of veins support one view or the other, and to what extent. In taking up the first point, I revert to the blocking out of the sources of internal heat mentioned above as 1B, 2B and 3B, which are essentially the same as those mentioned by Professor Van Hise in his "Principles" (*Trans.*, xxx., 49). The second and third points I have already discussed in my previous contribution.

1B. Doubtless the crushing of rocks under dynamic stress and chemical reactions develops heat, but to what extent I do not know, nor does this source seem to me to be capable of more than this general expression. The development of interior heat by chemical reactions shares the same indefiniteness.

2B. As to the part which the normal increase of temperature plays in aiding terrestrial circulations, it is possible to reach a more accurate quantitative expression. The heat which will raise the temperature of a column of water from 4° C. to 100° C. will produce an expansion of about 4 per cent. and a consequent diminution of density. This calculation is used, with subsequent general modification to meet terrestrial condi-

tions, by Professor Van Hise.* I brought against it the objection that this expansion would be neutralized by the pressure of the accumulating column of water, which, to a height of about 10,000 ft., would rest upon that portion which would attain a depth in the earth where the temperature would be 100° C. While I did not have at hand the data for an exact expression, I had submitted the proposition to a friend who could give an authoritative opinion and had been assured that the modification was well grounded. I stated, therefore, that it would practically prevent effective expansion and loss of density. This statement is too sweeping, and Professor Van Hise's objection in the Discussion† is well taken. Professor William Hallock has kindly given me the following references,‡ in which it is stated that the cubical compression of water at 4° C. is 0.0000469 per atmosphere. Assuming that this holds good for all temperatures up to 100° C., it means, in a column of 10,000 ft. in height, which would create a pressure of about 5000 lbs. to the square inch, a compression of about 1.6 per cent. at the base, leaving 2.4 per cent. of the original 4 there effective. If, again, the data given by Dr. Carl Barus, and cited by Professor Van Hise,§ are taken, the results are not greatly modified. Dr. Barus determined the compression of a capillary column of water, 17.4 c.m. in length and at a temperature of 23° C., to be, for 83 atmospheres, .0037; for 160 atm., .0075; for 226 atm., .0108. If we continue it at the same rate for 340 atm. (or 10,000 ft.), it is .0165 or 1.65 per cent. At 100° C., on a capillary column 18.1 c.m. long, Dr. Barus determined it to be, for 83 atm., .0046; for 180 atm., .0098; for 244 atm., .0133. Continuing at the same rate, it would be, for 340 atm., 1.84 per cent. at the base.

Since we assume that the increment of temperature and the increment of pressure are each uniform in descent, we may say that for an increment of 96° C. we have an expansion of 4 per cent., or $\frac{1}{24}$ of 1 per cent. for 1°. At the same time we have

* *Trans.*, xxx., 49, and *Genesis of Ore-Deposits*, p. 304.

† *Trans.*, xxxi., 296.

‡ W. Watson, *Textbook of Physics*, p. 182. Wüllner, *Lehrbuch der Physik*, vol. i., p. 275. Johann Müller, *Lehrbuch der Physik*, vol. i., p. 139.

§ *Trans.*, xxxi., 296.

a compression of 1.6 per cent., or, expressed in the rate per degree of increased temperature, $\frac{1}{60}$ of 1 per cent. The net expansion per degree expressed in per cents is therefore $\frac{1}{24}$ minus $\frac{1}{60}$ or $\frac{1}{40}$.

It is now not difficult to reach a quantitative expression of the actual efficiency of the normal increase in temperature in promoting hot-springs. We may assume a mean annual temperature at the surface of the earth of 10° C. For comparison, at New York it is 10.6. If a descending column starts at 10° and ends at 100°, its mean temperature will be 55°. Mr. G. K. Gilbert has found, as quoted by Professor Van Hise, that the waters of the hot-springs in the Cordilleran region range from 37° C. to 100° C., and that those of the much more abundant warm springs range from 18° to 37°. There is little doubt that many of these, and probably all the hotter ones, are connected with expiring vulcanism and have no bearing upon this immediate discussion. If, therefore, we assume springs emerging at 20°, 30°, 40°, and so on to 100°, we shall cover the essential cases in Nature. In the calculation we must use the mean temperatures of ascending columns which start at 100° C. and reach the surface at the above temperatures, and we may express the whole matter in a small table, recalling that, for each increase of 1° in the mean temperature of the uprising column, as compared with that of the descending one, there results an expansion of $\frac{1}{40}$ of 1 per cent., which, expressed in feet for a 10,000-ft. column, is 2.5 ft.

TABLE I.—*Mean Temperature of Descending Column, 55° C.*

Temp. of Emergence. Centigrade Degrees.	Mean Temp. of Ascending Column. Cent. Deg.	Excess of Temp. Cent. Deg.	Increase of Head.	
			Per Cent. Expansion.	Feet.
20	60	5	$\frac{1}{8}$	12.5
30	65	10	$\frac{1}{4}$	25.
40	70	15	$\frac{3}{8}$	37.5
50	75	20	$\frac{1}{2}$	50.
60	80	25	$\frac{5}{8}$	62.5
70	85	30	$\frac{3}{4}$	75.
80	90	35	$\frac{7}{8}$	87.5
90	95	40	1	100.
100	100	45	$1\frac{1}{8}$	112.5

When we consider how slight an increase this amounts to in a 10,000-ft. column, which is fed by all sorts of small tributaries with high friction; and when we compare the results with the vastly greater head resulting from inequalities of the ground which would almost pass unnoticed; when, again, we recall the rarity of hot-springs having even the moderately elevated temperatures and not obviously in volcanic or eruptive regions; and when we realize that any ascending column would inevitably draw to itself by induced currents much colder water in the rocks toward the surface, I think we are justified in practically dismissing the normal increase of temperature in the earth as of any essential importance in helping to force descending meteoric waters through the devious underground passages. We must have a head contributed by a higher source at the point of entry, and therefore a continuous column of water, or we must have local supplies of heat from recently intruded igneous rocks.

Again, if we have a region where the rate of increase of the interior temperature is less than the basis of the above calculation, viz., 1° C. for each 30 meters (1° F. for each 55 ft.), as, for instance, Keweenaw Point, where the rate is very nearly 1° C. for 60 meters (1° F. for each 100–110 ft.), or the Transvaal, where, as I learn from Mr. Pope Yeatman, preliminary experiments have shown an even slower rate, then the force of my argument is doubled. And if the mean annual temperature is higher than 10° C., the argument is thereby correspondingly strengthened. Naturally, also, a colder mean annual temperature weakens the argument, but not proportionately, since water is densest at 4° C., leaving a range of but 6° for mean annual temperature as between this and the 10° assumed above, before the limit is reached.

I realize that the expulsive action of the normally heated interior was only a minor point in Professor Van Hise's argument, and it is not with reference to his paper that these conclusions are specially urged, but because it is probable that generally, among geologists, much greater efficiency is attributed to this agent than it would seem to deserve. All these considerations make us fall back with the greater reliance on igneous rocks as sources of heat and energy for promoting circulations

which reach the surface. The influence of the increase of temperature in the normal ratio must be mainly one of magnifying chemical efficiency in those meteoric waters which come within its influence.

In this connection I cannot refrain from referring with the greatest admiration to Mr. Weed's recent paper on "Mineral Vein-Formation at Boulder Hot Springs, Montana."* It is of the highest significance, both in reference to the topic here discussed and to the one next to be taken up.

3B. If we imagine a mass of molten igneous rock injected from below into the upper regions where the meteoric groundwaters exist, a new factor is introduced of enormous efficiency. The molten rock may be considered as having a temperature of about 1200° C. (about 2200° F.). Its influence in expanding to the full limit of the liquid condition any meteoric waters within the sphere of its influence would be relatively abrupt, and its effect in increasing normal head would be pronounced. If it sufficed to change to vapor any of these waters, their density would be enormously lowered and the head would be still more effective. But even apart from the head of the descending column, and even without assuming its existence with reference to waters at the place in question, for meteoric waters may be present even if not under a continuous column to the surface, the expansive force of the steam, or even of the dissociated gases, reinforced by the copious emissions of the eruptive, would start circulations toward the surface, and, as it seems to me, would be a most efficient agent. This is what I have referred to in my paper and elsewhere as contributions of energy, and the process has been indicated by describing intrusive rocks as stimulators of circulation.

Gradually the intrusive rock cools and becomes a less and less efficient cause, and in the end it assumes the normal temperature for that portion of the earth in which it is situated. Possibly circulating waters continue their migrations, urged on by head, and are effective in depositing ores. Possibly, also, they practically cease, and the period of ore-deposition corresponds to the period of efficiency of the eruptive. I am

* *Twenty-First Annual Report U. S. Geol. Survey*, II., 227.

strongly inclined to believe the latter view is correct, and that when the fires under the boiler are quenched, the engine ceases to run.

Do we, then, find mineral veins provided with ores in those places where, once in a million times, the combination of precipitating agent and metalliferous solution meet under favorable conditions in the circulation of the meteoric ground-waters? or do we find them where, down under the surface, some intrusive rock has entered charged richly enough with a metallic burden to impart it to uprising heated waters and yield a series of ore-bodies? From the experience gained in western mining-districts the latter appeals to me the more forcibly, and I am inclined to believe that original ore-deposition ceased, not so much because cementation plugged the conduits as because the energy of the stimulating cause became exhausted. But even in making this guarded statement, I trust that I do not fail to appreciate the extent to which the whole matter is speculative and inferential,—a phase of the subject adequately emphasized, and I think alone adequately emphasized, in my previous paper.

There remain but one or two other points which seem to me to deserve attention beyond the treatment given them in the "Rôle of the Igneous Rocks, etc." There is some difference of opinion between Professor Van Hise and myself regarding the abundance of veins. While I have the greatest respect for his very wide experience and observation, I nevertheless am strongly of the opinion that, if we leave out pegmatites and their related quartz-veins, which are so extensively developed in metamorphic districts, veins of any sort, commensurate in size with those which we mine, are quite rare phenomena, and, though locally abundant, are yet, on the whole, but seldom seen. This is not alone my own opinion, but that of friends in the practice of mining engineering, and of greater experience in these matters than either Professor Van Hise or myself. Unless some very restricted cause has occasioned them, they ought to be far more abundant than they are.

As to the presence of the ground-water in all mining-regions, an additional word may be of interest. There certainly are localities in the arid region of the West where, at considerable

depths, it has not yet been met in notable amount, and where its distribution is very irregular. At Tintic, Utah, for instance, as I am informed by Dr. W. P. Jenney, the Mammoth-Tintic workings are 2000 ft. deep in the limestone. They have never used a pump nor have had more than a little drip of water in a few places. The ores are oxidized and the bottom levels are perfectly dry. The ground-water may be encountered in time, but it is certainly very deep. One or two miles away, in the monzonite, water is met within 100 or 200 ft. of the surface—not in great quantity, indeed, but sufficient to have prevented the oxidation of the ore. Over the divide from the Mammoth, and beginning 550 ft. below it, are the Bullion-Beck and Gemini mines. Their shafts are down 1660 ft., and from very large and extended workings, and of course with no attempt to impound the water near the surface, they gather about 10 gallons a minute,—no more than can be readily removed by a bailer once in a while through the day. The ores are all oxidized.

The Horn-Silver mine at Frisco is down 1600 ft. and is practically dry; the ore is oxidized. Water for the camp is, of necessity, brought in from a distance. I realize that Mr. Emmons has stated in his paper* that some water is met, but the quantity is so small that the present management is sinking a bore-hole from the bottom of the mine in the hope of tapping enough, at least, to furnish a supply for the boilers.

My friend, Mr. John N. Judson, has given me some interesting notes on the Mapimi mines in Mexico. The mines were dry to a depth of over 760 meters, or about 2400 ft. Some dampness was first observed in the wall-rock, and later some water appeared in the veins, which are chimneys in limestone. Whether the workings will pass through this wet ground (it is not very wet) and again reach dry rock will be one of the interesting things for the future to determine.

In a review of the separate volume on "The Genesis of Ore-Deposits," recently issued by the Institute, Mr. H. F. Bain, in the *Journal of Geology*, May–June, 1902, p. 434, emphasizes

* "The Delamar and the Horn-Silver Mines," by S. F. Emmons, *Trans.*, xxxi., 658.

the importance of considering, in this connection, only vertical depths, and not the relatively flat inclines, which, while long and perhaps dry, may not attain great depth nor be significant. I believe all the cases cited by me have been of vertical shafts. Mr. Bain also mentions experience in the Newhouse tunnel, in cutting wet veins, as indicating the presence of water at great depths. To this, however, it may be replied that a tunnel into a mountain merely produces an artificial spring; that springs exist along almost all valleys, and their water at times certainly comes from considerable depths; but my contention is that, so far as actual experience goes, in very deep mining, water is scarce or almost unknown unless there is expiring vulcanism. From this it follows that the igneous rocks are probably the important factors in deep circulations.

Regarding points like these, it is most desirable that members of the Institute should place observations on record.

In closing, I may add that, although I apparently differ with Professor Van Hise regarding the relative importance of certain factors in the problem, there is no one who has a higher admiration for his essay than myself, a feeling which, as a matter of fact, I had elsewhere expressed before the Richmond meeting. At the same time, a somewhat extended correspondence has shown that not a few mining-geologists in America and elsewhere are in sympathy with the points emphasized in my paper, and with the relative importance there attached to the several factors.

No. 11.

A Consideration of Igneous Rocks and their Segregation or Differentiation as Related to the Occurrence of Ores.*

BY J. E. SPURR, CONSTANTINOPLE, TURKEY.†

(New York and Philadelphia Meeting, February and May, 1902. *Trans.*, xxxiii., 288.)

CONTENTS.

	PAGE
INTRODUCTION,	252
I. THE RELATION OF ORE-DEPOSITS TO IGNEOUS ROCKS IN GENERAL,	253
II. THE DISTRIBUTION OF METALS IN SEDIMENTARY ROCKS,	254
III. THE SEGREGATION OR DIFFERENTIATION OF IGNEOUS ROCKS,	259
IV. THE ORDER OF CRYSTALLIZATION OF MINERALS IN IGNEOUS ROCKS,	263
V. THE FORMATION OF MINERAL SEGREGATIONS IN MOLTEN MASSES,	264
VI. THE UNKNOWN FINER LAWS OF ROCK-SEGREGATION,	265
VII. THE PRESENCE OF METALS IN THE IGNEOUS ROCKS,	266
VIII. THE CONCENTRATION OF COMMERCIALLY-VALUABLE MINERALS BY SEGREGATION WITHIN MOLTEN MASSES, PREVIOUS TO THEIR CONSOLIDATION,	267
1. *Iron*,	267
2. *Chromium*,	267
3. *Nickel*,	268
4. *Cobalt*,	269
5. *Platinum*,	269
6. *Copper*,	270
7. *Gold*,	271
IX. THE ORIGIN OF CERTAIN GOLD-QUARTZ VEINS,	271
1. *Evidence as to the Origin of Quartz-Veins as Magmatic Segregations*,	275
2. *The Genetic Connection of Gold-Quartz Veins with Siliceous Igneous Rocks*,	279
3. *The Subordinate Connection of Gold-Quartz Veins with Basic Igneous Rocks*,	284
X. RÉSUMÉ OF THE EVIDENCE CONCERNING THE PREFERENCE OF CERTAIN METALS TO ACCUMULATE, BY MAGMATIC SEGREGATION, IN CERTAIN ROCK-TYPES OF THE ESTABLISHED CLASSIFICATION,	284
1. *Basic Rocks*,	285
2. *Siliceous Rocks*,	285
XI. THE RELATION BETWEEN ORE-DEPOSITS DUE TO MAGMATIC SEGREGATION AND OTHER ORE-DEPOSITS,	286
XII. THE SEQUENCE OF VOLCANIC ERUPTIONS, CONSIDERED IN CONNECTION WITH THE SEQUENCE OF METALLIFEROUS VEINS,	288
XIII. THE PERSISTENCE OF PETROGRAPHIC PROVINCES, CONSIDERED IN CONNECTION WITH THE PERSISTENCE OF METALLIFEROUS PROVINCES,	291
XIV. CONCLUSION,	299
POSTSCRIPT,	301

* Published by permission of the Director of the U. S. Geological Survey.

† Since returned to the United States, and now again in the service of the U. S. Geological Survey.—R. W. R.

INTRODUCTION.

IN a new field like that of the study of ore-deposits, it is hard to keep all sides of the question in sight at once; to realize that the laws worked out for certain types of ore-deposits in one region do not apply to deposits of apparently similar ores the world over. Thus have arisen our most hotly-contested controversies, over such questions, for instance, as: Whether bedded ores are mechanical sediments formed at the same time with the enclosing rock, or were introduced later by solution; Whether metals have been deposited by ascending or by descending waters; Whether they are derived from the immediate wall-rock, from the rocks of the whole district in which they occur, or from the "barysphere"; Whether they are deposited in pre-existing cavities or are replacements; and so on.

The researches of the past score of years or so have rather dampened the heat of these discussions. Investigators have been led to recognize in nature a complexity which permits most of the advocated theories to find their place as factors mutually co-operating to constitute the intricate system which determines the occurrence of ores as we now find them. I think most of us agree with Prof. Van Hise,* that "for many ore-deposits a complete theory must be a descending, lateral-secreting, ascending, descending, lateral-secreting theory." Indeed, all this—and more!

Van Hise's discussion of the work of underground water in forming ore-deposits seems to me the best general contribution of recent years, not excepting the famous treatise of Posepny. A masterly discussion like this fills, for the moment, the whole mind of the reader, and he might thus fail to consider the importance of principles which the author has purposely omitted. Kemp, Lindgren and Vogt, in their discussions of Van Hise's paper, have called attention to certain of these principles, especially those involving the connection of igneous rocks with ore-deposition, or *ore-segregation*, as I would like to call it.

It is concerning this part of the field that I wish to present some considerations, limited in extent and detail by my lack of

* "Some Principles Controlling the Deposition of Ores," *Trans.*, xxx., p. 173. *Genesis of Ore-Deposits*, p. 428.

access to a wide range of literature, and by the difficulty of the subject itself. With most of Van Hise's conclusions, I may remark, I fully agree.

For the ideas herein set forth I can claim, of course, only a certain amount of originality. It will be seen that my views (which I have previously announced, although not in such compact form as this*) resemble, more or less, those of Lindgren† and Kemp‡ in this country, and De Launay, Beck and Vogt§ in Europe, but especially the last named.

I. The Relation of Ore-Deposits to Igneous Rocks in General.

Two important points have come to be agreed upon by most of the best writers on ore-deposits, namely: (1) That ores in general were *originally* derived from igneous rocks; and (2) that *present* ore-deposits are closely associated with actually-exposed eruptives.

Probably at least nineteen out of twenty important ore-deposits (excepting those of iron) are acknowledged to have a genetic connection with associated rocks of igneous origin. Especially well-marked is the connection of *ore-regions* or *zones* with areas or belts of igneous activity.‖ The interdependence of eruptive rocks, hot springs and many ore-deposits has at last attained the dignity of a general law.

The hot springs often owe their heat, and hence their upward propulsion, to igneous masses, while the ore-deposits are the direct work of both the other two, the material being largely derived from the rocks and the concentration being effected by the waters. Moreover, the lines of weakness (of

* J. E. Spurr, "Economic Geology, Mercur Mining District, Utah," 16*th Annual Rpt. U. S. Geol. Surv.*, Part II., pp. 395, 449 (1895); "Geology of the Yukon Gold-District," 18*th Annual Rpt. U. S. Geol. Surv.*, Part III., p. 297 (1898); "Quartz-Muscovite Rock, from Belmont, Nevada," *Am. Jour. of Sci.*, 4th series, vol. x., Nov., 1900, p. 355.

† Waldemar Lindgren, "Character and Genesis of Certain Contact-Deposits," *Trans.*, xxxi., p. 226, and *Genesis of Ore-Deposits*, p. 716.

‡ J. F. Kemp, "The Rôle of the Igneous Rocks in the Formation of Veins," *Trans.*, xxxi., p. 169, and *Genesis of Ore-Deposits*, p. 681.

§ J. H. L. Vogt, "Problems in the Geology of Ore-Deposits," *Trans*, xxxi., p. 125, and *Genesis of Ore-Deposits*, p. 636.

‖ J. F. Kemp, "The Rôle of the Igneous Rocks in the Formation of Veins," *Trans.*, xxxi., 196, 197, and *The Genesis of Ore-Deposits*, pp. 707–709.

faulting, etc.) determined by, or at least coextensive with, the intrusion of the molten masses, frequently form the channels of the springs, and thus operate to restrict the ore-deposits to the eruptive zones.

The broad explanation of this association is plainly contained in the proof which we now possess, that the eruptive rocks contain in varying amounts the rarer elements (among them, most of the metals), in addition to the common ones.

In the stratified rocks, on the other hand, the metals, though present, seem to be in general less abundant.*

II. The Distribution of Metals in Sedimentary Rocks.

All sediments were probably derived in the beginning from the destruction of igneous rocks, but the elements thus derived attain through mechanical and chemical surface agencies a degree of concentration hardly equalled in the igneous rocks themselves. Thus calcium becomes concentrated into limestones, and silicon into great volumes of sandstone or quartzite. Among the commercially valuable minerals, salt, gypsum, phosphate of lime, borax and others have thus become concentrated. These facts indicate that metals also must be similarly dissolved out and dispersed. In the case of some of the metals, we know that they are re-deposited in concentrated form. By chemical and mechanical action, iron is concentrated in bogs, in greensands, and in ferruginous shales and sandstones, there to yield, after some further concentration, such notable deposits as the iron-ores of the Lake Superior region. By chemical action, manganese is concentrated, not only in bogs, but on a large scale in marine sediments, such as shales and limestones, so that most of the commercially important deposits are derived, through the medium of further concentration, from these sources. By mechanical and chemical action such rarer metals and minerals as gold, platinum, diamond, tin-ore, monazite, garnet, etc., are very highly concentrated in river channels and in marine shore-deposits. Examples of the enormous efficiency of surface concentration in producing valuable deposits of the rare metals are furnished

* J. F. Kemp, "The Rôle of the Igneous Rocks in the Formation of Veins," *Trans.*, xxxi., p. 175, and *The Genesis of Ore-Deposits*, p. 686.

by the world's gold-placers, the Cape Nome beach-sands, and (according to some authorities) the South African auriferous beds. As regards platinum, nearly *all* the known concentrations, so complete as to be commercially valuable, have been effected by surface-agencies.

But, on the one hand, iron and manganese are common elements; and, on the other hand, gold, platinum, tin-stone, etc., are relatively insoluble; and thus their concentration may be explained. Concerning the metals (such as silver, copper, lead, zinc, arsenic, antimony, etc.), which are at the same time relatively rare and relatively soluble, no such satisfactory conclusion has been reached. That, upon disintegration of the igneous rocks, these metals largely go into solution in surface-waters, there is no doubt. These waters (apart from those which pass underground, where we know that the metals are frequently precipitated in concentrated form*) find their way into lakes, and especially into the oceans. What becomes of the metals which they hold in solution?

Are they precipitated either in concentrated or in evenly disseminated form, or do they remain in solution? If it be true, as I think it is, that a sedimentary rock, *as a rule*, contains much smaller proportions of the metals than an igneous rock,† we must conclude that these metals are not *evenly* precipitated. Yet I find it impossible to believe that all of these metals contained in the igneous rocks which have been, ever since the solid world began, going to pieces to form the enormous bulk of known sediments, can have been stored in the sea-water and are there still.

Most of the elements—especially silver, copper, iron, manganese, and gold—have been chemically detected in sea-water; but they are present only in minute traces; whereas the total amount of metals which has passed into the sea in solution during the ages of erosion and deposition must be

* C. R. Van Hise, "Principles Controlling Deposition of Ores," *Trans.*, xxx., p. 138 *et seq.*, and *The Genesis of Ore-Deposits*, p. 393.

† J. F. Kemp, "The Rôle of the Igneous Rocks in the Formation of Veins," *Trans.*, xxxi., 174, says it appears, from analyses of both the sedimentary and the igneous rocks of Missouri for lead and zinc, that the igneous rocks are, as a rule, richer by one place of decimals than the former. F. Posepny, in *The Genesis of Ore-Deposits*, p. 122, says that innumerable analyses of marine sediments and precipitates, especially of limestones, have failed to show traces of metals.

many times in excess of the solvent power of the water at any one time, and vastly in excess of the dissolved amount now contained therein. We must, therefore, confess that, besides the metals mechanically laid down in slates and conglomerates, derived directly from the abrasion of igneous rocks, the same metals have been chemically precipitated somewhere from marine and other surface-waters. Indeed, the researches of Malaguti, Bibra and Forchhammer* long ago established the fact of such precipitation by finding traces of metals in the ashes of marine plants, and in the hard parts of marine animals, such as corals. Among the metals mentioned above as having the question of their concentration at the surface still undecided, lead, zinc, cobalt and nickel have been thus detected.

Since, therefore, the metals in question (notably lead, zinc, silver and copper), which are both relatively soluble and relatively rare, after being extracted from the igneous rocks during the process of weathering, transportation and sedimentation, have neither been uniformly deposited in the sediments nor accumulated in solution, I am forced to believe that, like the commoner elements (among them the commoner metals) already mentioned, they have been (probably by chemical precipitation) deposited in certain places as *concentrations*, which are, as a rule, relatively richer than the igneous rocks in which the said substances were originally disseminated.

The hypothesis that bedded ores have sometimes been deposited contemporaneously with the enclosing sediments has been, of late, distinctly out of fashion, and justly so, in the exclusive sense in which it has sometimes been held. Bischof, reasoning from the traces of metals in sea-water, believed that their precipitation as sulphides was possible, and thus explained the occurrences of copper and silver sulphides in the Permian *Kupferschiefer*, and of lead sulphide in the *Buntsandstein*.

Groddeck advocated the same idea, and advanced the theory that certain horizons are especially ore-bearing.† Hoefer has applied this explanation to the lead- and zinc-deposits of Upper

* *Chem. u. Phys. Geologie*, vol. i., Bonn, 1863, pp. 445–7. C. G. Bischof.

† Posepny, *Genesis of Ore-Deposits*, first edition, p. 112, etc.; second edition, p. 122.

Silesia and other districts, which occur in Triassic marine limestone. In Bohemia and the Urals, as in the German *Kupferschiefer* district, the Permian rocks contain copper in many places; in Utah and New Mexico (in the Silver Reef and Nacimiento districts, etc.) the Triassic sandstones contain copper and sometimes silver; in the Permian of Texas there are three copper-bearing zones, extending over three counties.*

These are examples of numerous deposits which have been described by some able investigators as due to deposition contemporaneous with the enclosing beds, while, in every case, this conclusion has been repeatedly and vigorously contested. The fact is that in every one of these instances the ore-deposits have an evident genetic connection with fissures, joints, dikes, etc., of later age than the rock; and hence it is argued that the ores (including those disseminated in the rock) have been introduced through these fissures.

I need hardly point out that this conclusion is not logically valid. I confess that, after visiting the Mansfeld deposits, I was so impressed by the evident connection of the faults with the ore-bodies, and by the frequent proofs of the formation of minerals more recent than the country-rock, that I came away quite satisfied that the idea of contemporaneous deposition was old-fashioned and untenable. Yet neither there nor elsewhere does this opinion certainly follow from the observed facts. The present ore-bodies in most of these districts—perhaps in all—are largely secondary concentrations, due to percolating waters, and are hence found along water-channels, as held by Posepny and others; but this does not affect the question whether these waters brought up the metals with them "from below" or concentrated them from disseminations contemporaneous in deposition with the strata. In view of what I have stated above, I am now inclined to hold the latter view.

Among the detrital rocks, slates are known to contain marked quantities of the metals in question. Frick, Forchhammer and Sandberger found copper, zinc, lead, arsenic, antimony, tin and cobalt in clay-slates. These are, very likely to a large extent, mechanical concentrates from the rocks by the

* Kemp, *Ore-Deposits of the United States*, third edition, p. 224, etc.

destruction of which the slates originated; yet they are probably also, in some degree, chemical precipitates.

The Mediterranean has been found to contain copper in solution in the proportion of at least 0.01 gramme to the cubic meter. Philips* says that "the black and usually very sulphurous matter deposited in basins where sea-water has been left to itself constantly contains copper, and the same is generally true with regard to the dark-colored gypseous muds of all ages."

Most *chemically precipitated* rocks† certainly seem to be much poorer in original metallic contents than the fragmental ones. The limestones of the Mississippi valley have been shown to contain lead and zinc, disseminated in small quantity; and it is the conclusion of Whitney, Chamberlin, Winslow and others that the ore-deposits have been concentrated from these disseminations. But these limestones appear to contain the metals in smaller quantity than do the older igneous rocks of the region, so that the dissemination in the limestones can hardly be regarded as a *concentration.* (See footnote, p. 255.)

With these and other facts in mind, we cannot safely give up the idea that metals have been concentrated by surface agencies in favorable places and times, and, consequently, that certain strata (possibly also, and restrictedly, certain geologic periods) are, by reason of their original metallic contents, more favorable than others to the occurrence of ore-deposits. I would even hesitate equally to deny or to affirm that there is a connection between the Triassic and Permian red sandstones and certain copper-deposits. Yet we must be careful not to rush into any such hasty generalization as that of Sir Roderick Murchison, who believed that most auriferous rocks are of Silurian age,‡—an obsolete idea which I have nevertheless found in one of our latest works on the metallurgy of gold.§

The concentration of metals by surface agencies, though a fascinating study, is out of place in the special inquiry to which this paper is devoted—that of concentration by segregation within molten rocks.

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* Phillips and Louis, *Treatise on Ore-Deposits*, 1896, p. 132.

† This phrase is meant to include limestones of organic origin.

‡ See Rickard's "Review," *Eng. Min. Jour.*, Oct. 19, 1901, p. 491.

§ Eissler, *Metallurgy of Gold*, 1900, p. 31.

III.—The Segregation or Differentiation of Igneous Rocks.

Having pointed out the generally-admitted fact that the larger number of ore-deposits have direct genetic connection with igneous rocks, I wish to describe one of the chief processes by which the different kinds of igneous rocks originate, which I believe has an important bearing upon the segregation of ores.

While it is known that igneous rocks may be formed directly from the fusion of sediments (in which case their composition is determined by the selective action of surface agencies), yet it is now widely accepted that many, perhaps most, of them owe their peculiarities of composition to a process of segregation which goes on within the molten masses of the earth's interior. The evidence for this process, and some of the details of it, have been pretty fully stated by the writer elsewhere,* and only a few points will be mentioned here. The line of argument is best seen if we proceed from examples on a small scale to successively larger ones. Thus, in the laboratory, materials intimately mingled in solution may separate into distinct crystals, or into segregated bunches of like crystals; and in veins the different minerals are often found bunched in the same way. Nearly every igneous rock shows irregularities of composition due to a similar clustering together of like minerals. These aggregations increase from microscopic size to the size of a man's head; and from these relatively small patches there is a gradation to larger rock-masses, which have marked differences in structure and composition from the rest of the igneous body, of which they, nevertheless, form integral portions. For example, the borders of dikes are frequently less siliceous, and contain more iron (and associated elements) than the interior of the same bodies. In still larger igneous masses, it is found that different portions have slightly different chemical, mineralogical and structural characters, while they all grade into one another. Again, it has been observed that in a given district different igneous rocks (such as volcanic rocks erupted at different times) are often closely related, and pass into one another.

* "Geology of the Yukon Gold-District," 18*th Ann. Rep. U. S. Geol. Surv.*, Part III., p. 300.

Finally, modern petrographic research and comparison have shown that the rocks of a large region, taken collectively, often present constant differences from those of neighboring regions.

All these phenomena may be explained by the observed fact that in the molten masses, as well as in solutions, there is a force inducing like elements to group themselves together.

Concerning the exact process by which the materials of the molten rocks are enabled to make such important migrations in order to cluster together, there is no certainty; and, indeed, for the purposes of this paper, it is hardly necessary to inquire. Until recently, it was common to appeal to Soret's principle of molecular flow, namely, that molecular concentration may be caused by differences of temperature. Mr. G. F. Becker,* however, has argued against the applicability of this law, on account of the slowness with which it operates. Mr. Becker† and the writer,‡ independently and at about the same time, called attention to the probable importance of convection currents in producing segregation. By these currents the minerals which first crystallize (namely, the heavier minerals, such as magnetite, olivine, hornblende, pyroxene, etc.) would be, to a greater or less extent, concentrated in the outer portions of igneous rock-masses, where they are actually often found.

The small segregations in igneous rock are usually either more siliceous or less siliceous (more "acid" or more "basic") than the enclosing rock; and extremely acid and extremely basic segregations are often found in close association This tendency of the molten mass to segregate its highly siliceous constituents from the rest has also been studied on a large scale, chiefly from the order of succession of lavas erupted at successive periods in the same district, or of dikes successively introduced. Brögger and Geikie,§ from extensive studies of eruptive rocks in Norway and in Scotland, respectively, both concluded that the rocks progressed from the more basic to the more acid varieties.

* "Some Queries On Rock Differentiation," *Am. Jour. Sci.*, Jan., 1897, 4th series, vol. iii., p. 21.

† "Fractional Crystallization of Rocks," *Am. Jour. Sci.*, Oct., 1897, p. 257.

‡ "Geology of the Yukon Gold-District," *18th Ann. Rep. U. S. Geol. Surv.*, Part III., p. 306.

§ J. P. Iddings: "The Origin of Igneous Rocks," *Bull. Phil. Soc. Wash.*, vol. xii., pp. 122, 145, 146.

Iddings's* work goes to show the normal law to be, that a rock of intermediate composition is followed by rocks progressively higher and, at the same time, by others progressively lower in silica (the more basic and the more acid varieties being associated and contemporaneous), so that the series begins with a mean and ends with extremes. This has been considered by the writer to hold good for the dike-rocks of the Forty-Mile district, Alaska,† and (a problem on a much larger scale) for the petrographic province of which the great basin of Nevada forms a portion.‡ In the case of the Forty-Mile dikes, the most siliceous varieties were found to be later than the most basic ones.

The laws thus deduced agree in this: That a molten rock, mass, under favorable conditions, tends to separate (segregate) into a more acid and a more basic portion; while the fact that the acid (siliceous) rocks characteristically follow, rather than precede, the basic (less siliceous) at any one period, joined with the other known principles of segregation, indicates that the change is effected at each stage by the separation and crystallization of the more basic constituents, leaving the more siliceous residue unconsolidated.

That the basic minerals in general crystallize first in a cooling rock has been proved by microscopic study. If the segregation is limited in time, and is broken into by such an occurrence as eruption and consolidation, the differences attained may be comparatively slight; but under favorable circumstances extremes may be reached. Thus, rocks consisting almost entirely of olivine, pyroxene, or hornblende, together with iron oxides and sulphides, may originate. On the other hand, rocks made up essentially of quartz and alkali feldspars (alaskites)§ may be formed, and these may pass by gradual transitions into quartz-veins, as will be dwelt upon later. An illustration of these different results is found in the

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* *Op cit.*

† "Geology of the Yukon Gold-District," 18*th Ann. Rep. U. S. Geol. Surv.*, Part III., p. 234.

‡ "Succession and Relation of Lavas in the Great Basin Region," *Journal of Geology*, vol. viii., p. 621.

§ J. E. Spurr: "Classification of Igneous Rocks," *Am. Geologist*, Apr., 1900, vol. xxv., p. 229.

dikes of the Forty-Mile region,* which consist of rocks closely related, being made up chiefly of hornblende, quartz and feldspar. Yet by gradual changes in the proportions of these minerals, rocks of all degrees of basicity and acidity are produced, terminating, on the one hand, in hornblendites (composed almost entirely of hornblende) and pyroxenites, containing pyrite, pyrrhotite, ilmenite and other metallic minerals; and, on the other hand, in alaskites, growing gradually more siliceous until they pass, with no break, into quartz-veins.

In the progress of segregation, we have seen that in the acid-gaining portion there is a continuous increase of silica, due to the constant precipitation and removal of the basic portions. There is also an attendant increase in the amount of water.

As is shown by microscopic and chemical study, all rocks contain water, but the molten material contains much more than the resulting rock. Most of this water is expelled at the moment of solidification, together with certain gases and a great variety of other materials held in solution.† When rocks cool at the surface, this escaping water forms the clouds of steam, highly charged with gases and minerals, which issue from fissures and other vents; but when they solidify below the surface the waters and gases are forced into the enclosing rock, producing the recrystallization and rearrangement of its constituents, called contact-metamorphism. This is chiefly confined to the contacts of siliceous igneous rocks, being especially remarkable around intrusive masses of granite, where it occupies a zone which, in extreme cases, may be several miles in width.

It seems, therefore, that the molten material from which siliceous rocks solidify contains more water than the basic material. Therefore, we may believe that by the progressive separating out of the more basic constituents the residual portion of a molten mass becomes more aqueous and more siliceous. Thus the peculiar form (often in lenses, not visibly communicating with large bodies of igneous rocks) and coarse crystallization of pegmatites are explained; for these rocks are near the end-product of the siliceous series; and the pegmatic

* "Geology of the Yukon Gold-District," 18*th Ann. Rep. U. S. Geol. Surv.*, Part III., p. 233.

† Daubrée, *Géologie Expérimentale*, Paris, 1879, p. 152.

rocks, by the disappearance of feldspar and mica, grade into pure quartz-veins, which show by their structure that they have been deposited from solutions so attenuated that they may best be described as waters highly heated and charged with mineral matter in solution.

By this process of rock-differentiation, concentration is continually effected through the segregation of like materials. Most of these materials are not commercially valuable. Thus the frequent segregation of masses of nearly pure hornblende, pyroxene or quartz has no lively interest for the miner. But when (as often happens) such segregations are feldspar or mica, they may acquire economic importance. And if the commonest of rock-constituents may be thus concentrated, other substances may be, also. In the basic Forty-Mile dikes, mentioned above, there was so large a proportion of ilmenite, magnetite, pyrrhotite and other metallic minerals that small pieces of the rock were drawn by the magnet. A slight further concentration would give commercially valuable masses; and there is good evidence that, in other districts, many such masses have originated in this way.

IV. The Order of Crystallization of Minerals in Igneous Rocks.

The process of segregation, which we have considered on a large scale, with the progressive precipitation of basic ingredients and the leaving behind of the siliceous ores, is recorded on a small scale in the internal structures of igneous rocks, as studied under the microscope.

Under this head I cannot do better than quote Prof. J. F. Kemp,* who says:

"Microscopic study of the igneous rocks has shown that, with few exceptions, the rock-making minerals separate from a fused magma on cooling and crystallizing in a quite definite order.† Thus the first to form are certain oxides, magnetite, specular hematite, ilmenite, rarely chromite and picotite, a few silicates, unimportant in this connection (zircon, titanite), and the sulphides, pyrite and pyrrhotite. Next after these metallic oxides, etc., the heavy, dark-colored basic silicates, olivine, biotite, augite, and hornblende, are formed. All these minerals are characterized by high percentages of iron, magnesium, calcium and aluminum.

* *Ore-Deposits of the United States and Canada*, 4th ed., p. 33.

† H. Rosenbusch, "*Ueber das Wesen der körnigen und porphyrischen Structur bei Massengesteinen*," *Neues Jahrbuch*, 1882, ii., 1.

They are very generally provided with inclusions of the first set. Following the bisilicates in the order of crystallization come the feldspars, and after these the residual silica, which remains uncombined, separates as quartz."

V. The Formation of Mineral Segregations in Molten Masses.

It has been shown that in the process of segregation in molten masses there is a recognized tendency to split up into more siliceous and less siliceous portions. The basic materials thus concentrated may be the almost exclusive constituents of the resulting rocks. Thus there are not uncommonly rocks made up essentially of the dark, heavy, basic, ferro-magnesian minerals, biotite, olivine, pyroxene and amphibole, with metallic minerals, such as magnetite, ilmenite, etc., in smaller amounts. The acid materials likewise may form rocks without important admixture of the basic ones, as in quartz alkali-feldspar rocks (alaskite), or in rocks made up almost entirely of alkali-feldspar (sanadinite, albitite, etc.). Further, as already pointed out, the constituent minerals may separate out from the mixture and the like crystals may group themselves together. Thus, there are rocks consisting almost entirely of olivine alone (dunite), of hornblende alone (hornblendite), of pyroxene alone (pyroxenite), of orthoclase feldspar (sanadinite), of soda-feldspar (anorthosite), and of lime-feldspar (anorthite rock). This completes the roll of the commonest rock constituents, save the micas and quartz. Although mica forms small segregations in igneous rocks, the writer is not aware that it occurs as the only essential mineral in any considerable mass of such rock. Quartz also appears at first sight to be an exception; but the writer will try to show later that this is not so, and that many considerable masses and veins of quartz are the result of segregation from the same molten material that produces other igneous rocks.

Besides these commonest original or primary minerals, there are others which are commonly present in marked quantity in almost every fragment of igneous rock. Perhaps the most important of these is magnetite, which is found in nearly all rocks. Besides this, there are other common metallic minerals, such as pyrite, ilmenite and pyrrhotite—all iron minerals. Chromite is rarer. Among the non-metallic accessory min-

erals, zircon, titanite and apatite are perhaps the most important. All of these less common minerals (as well as others not mentioned) are known to segregate, to a certain extent at least, so that they are many times more abundant in some rocks than in others.

This being the case, it is natural that the still rarer minerals and elements also should segregate, and should be found in certain rocks in far larger quantity than in others; and, indeed, this is known to be the fact.

VI. The Unknown Finer Laws of Rock-Segregation.

If there were invariable associations between certain rocks and certain valuable minerals, prospectors and miners would probably have detected it long ago, especially as regards the metals. But in the majority of cases the exceptions, to any rule we may be tempted to construct, are so numerous that we abandon the attempt. That this fact, however, does not contradict the conclusions above reached in regard to the preferential segregation of these minerals into certain rocks will appear when we consider how we name and distinguish the rocks themselves. The existing classifications of rocks are all based upon the relative content of the common constituents, the rarer ones being necessarily disregarded. The divisions, granite, syenite, dunite, diabase, basalt, phonolite, and the whole legion of others, are (apart from considerations of structure, age, mode of occurrence, etc., which have for the moment no bearing on this discussion) founded upon the presence and relative proportions of the ordinary minerals quartz, the various feldspars and feldspathoids, olivine, mica, amphibole and pyroxene. Even in classifications based upon the chemical composition of the whole rock, the component minerals being lumped together for analysis, only certain ordinary elements are taken into account, and the rock is assigned to its place upon the basis of the relative proportions of silicon, aluminum, iron, calcium, magnesium, sodium and potassium. Rock-divisions based on these elements do not necessarily connote the presence or absence of any others. For example, a petrographer finding a certain igneous rock knows at once that this rock is unusually rich in calcium, sodium, aluminum or silicon; but he does not know if it contains more or less than the average quantity of lead,

silver or mercury. Each element follows its own independent law of segregation, and disregards the established rock classification. Even with the commoner minerals and elements upon which this classification is roughly based, the variations are so wide as to lead the petrographer into grave difficulties. Thus, among the rocks which have been called *gabbro* we may find some consisting almost entirely of feldspar, and others made up chiefly of pyroxene. One of the commonest chemical divisions of the rocks is into acid, basic and intermediate kinds, essentially according to the proportion of silica present; but rocks of different mineralogical composition may have the same acidity. The basic rocks are rich in ferro-magnesian silicates, and so should be exceptionally strong in magnesia; but occasionally cases may be found where gabbro shows less magnesia than granite.

We can hardly expect, therefore, that the identification of a rock-species, under the accepted classification, will be of much help in guiding us to a knowledge of the relative content of the rarer elements. To arrive at such a knowledge, we should have a classification based principally upon the content of these rarer elements, and recognizable in practice by easy physical and chemical marks. But this is clearly impracticable.

In this difficulty, we may be helped to some extent by the principle which underlies the laws of chemical affinity and the association of minerals. Elements and minerals have tendencies to cluster in groups marked by some common characteristics; each element or mineral prefers to associate with certain elements or minerals rather than with others. This law of selective association has long been recognized by the geologist and the chemist. So it seems reasonable that among the rare elements and minerals not considered in rock-classification, some may have such strong preferential association with certain of the commoner rock-constituents on which this classification is based that we may be able to see some connection, even if a rude one, between these rarer constituents and the established rock-types.

VII. The Presence of Metals in the Igneous Rocks.

Iron is present—often in high percentage—in nearly every igneous rock. It occurs not only in the dark ferro-magnesian

silicates, but also as oxides and sulphides, as hematite, magnetite, ilmenite, pyrite and pyrrhotite.

Chromium, in the form of chromite and picotite, chrome-diopside, etc., occurs in marked quantities as an original constituent of many basic igneous rocks. Manganese is present in nearly every igneous rock, as a not unimportant constituent of the ferro-magnesian silicates. The rarer metals, lead, copper, zinc, tin, antimony, arsenic, nickel, cobalt, silver, gold, and the still rarer ones, have all been repeatedly found in fresh igneous rocks, particularly in the dark bisilicates.

VIII. The Concentration of Commercially-Valuable Minerals by Segregation within Molten Masses, Previous to their Consolidation.

1. *Iron.*

The fact that iron is unequally distributed in igneous rocks is well known. Many highly siliceous rocks (acid granites, alaskites, etc.) have only a trifling quantity (often 1 per cent. or less), while the basic rocks may contain 10, 15, and even 20 per cent. of iron oxide. Of this iron, a part is generally in the form of magnetite, a mineral shown by the microscope to be thickly disseminated in many basic rocks. It is generally titaniferous, and grades into ilmenite. From the highly magnetiferous phases of ordinary basic rocks to a phase where the magnetite becomes the principal constituent is an easy step. Such are the occurrences at Cumberland, Rhode Island, at Taberg, in Sweden, and in many other places. At some of these localities the iron mineral may gradually increase so as almost to exclude the other constituents, as at Taberg; or it may quite do so, as in the anorthosites of Minnesota and elsewhere, forming masses of iron-ore. As to the origin of these ores by segregation within the molten masses previous to cooling, there is a practical unanimity of opinion.

2. *Chromium.*

Like iron, chromium has a very manifest uneven distribution in igneous rocks, being rare in the siliceous ones, while in many of the basic ones it forms a not insignificant constituent, especially in rocks containing olivine.* In these rocks its relations

* Zirkel, *Lehrbuch der Petrographie*, 2d ed., vol. i., p. 426.

to other minerals show that, like magnetite, it is one of the earliest to crystallize during consolidation. That the chromite may, in some portions of these rocks, become so abundant as to form the principal constituent, the rock being nevertheless in nearly the state in which it cooled from fusion, is an occurrence which we might expect from our knowledge of the selective segregation of other constituents, and one which has been repeatedly observed. Vogt* has described a fresh peridotite from Norway which was almost or quite rich enough in chromite to be worthy of exploitation. The most important occurrences of chrome-ore occur in serpentines, which can generally be shown to be the product of decomposition of basic igneous rocks, chiefly peridotites (olive rocks); and these deposits are considered by Vogt to be the result of segregation while the mass was molten (magmatic segregation), although they had been explained by others as due to after-actions which took place during the alteration of the fresh rock to serpentine, or even to pneumatolytic (vaporous) action at the time of the rock's consolidation. J. H. Pratt, after studying the chrome-ores of North Carolina, arrived at the same conclusion as Vogt for other regions, namely, that the ores were actually magmatic segregations. Kemp† favors the same origin for other chromite-deposits in the United States. The writer, after examining the chromite-deposits near Saloniki, Turkey (Macedonia), and also in Asia Minor, inclines to the belief that most of these deposits have originated as magmatic segregations from the enclosing peridotitic rock.

3. *Nickel.*

Nickel occurs as an original constituent of some olivines‡ in basic igneous rocks. It is also found in more considerable amount in pyrrhotite, an iron sulphide which is frequently a primary mineral in igneous rocks and one of the first to crystallize on consolidation. Nickel occurs also as an alloy with native iron, in meteorites and in basalt.

In certain igneous rocks—as, for example, in the peridotites of Douglas county, Oregon, and of Webster, North Carolina—nickel is much more abundant than in others of the same petro-

* Quoted by J. F. Kemp, *Ore-Deposits of the U. S. and Canada*, 4th ed., p. 413.
† *Op. cit.*, p. 415. ‡ Dana, *System of Mineralogy*, 6th ed., p. 453.

graphical character. In the instances named, the nickel, upon the weathering of the rock, separated out as nickel silicate, and became concentrated sufficiently to be of possible economic importance.

Although these ore-deposits are immediately due to circulating surface-waters, which have accomplished a second concentration, the first and most important concentration was that which brought together unusual quantities of nickel in these particular rocks, and this was plainly done by magmatic segregation.

It has already been noted that pyrrhotite, like the other early crystallizing metallic minerals, may become abundant as a primary constituent of igneous rocks—as, for example, in the case of the Forty-Mile creek dike, already mentioned.* Cases where niccoliferous pyrrhotite in basic igneous rocks, evidently a primary constituent, gradually increases so as to form compact masses and to become a valuable ore, have been described on the best authority.

Of such origin (partly, at least) seem to be the niccoliferous pyrrhotites of Sudbury, Ontario, and those of the Gap mine, Lancaster, Pennsylvania.†

4. *Cobalt.*

This metal has the closest associations with nickel, and the general conclusions arrived at for the one are probably to a considerable degree good for the other. Like nickel, cobalt is present in perceptible quantity in certain basic igneous rocks, where it has been identified as occurring in olivine,‡ and, alloyed with native iron, nickel and copper, in Greenland basalt.

As yet, however, we have not sufficient reliable data to determine whether any important cobalt-ores are formed *principally* by magmatic segregation.

5. *Platinum.*

Platinum, in perhaps the majority of cases, is found closely associated with chromite or nickel, or both. Like these minerals, it is almost invariably genetically connected with basic

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* See p. 263.

† J. F. Kemp, *Ore-Deposits of the United States and Canada*, 4th ed., p. 431.

‡ Dana, *System of Mineralogy*, 6th ed., p. 453.

olivine rocks, or with the serpentine-rocks arising from the alteration of these. As an original constituent in basic igneous rocks, it is said to have been found both by Daubrée and Engelhardt. More recently, native platinum has been discovered in igneous rocks in the Urals, in the Nizhni-Tagil district, and the Goroblagodat district. These are extremely basic peridotitic rocks, containing large amounts of magnetite and chromite, besides platinum. According to Inostranzeff, the platinum occurs as grains and leaves in the chromite. In the Goroblagodat district, while the peridotites contain by far the larger amount of platinum, Saytzeff found the metal as an original constituent in other igneous rocks also, such as porphyrite, gabbro-diorite, and syenite-gneiss. Mr. C. W. Purington also obtained, on crushing and panning the peridotite of this district, many fine colors of platinum.* The writer has also had the privilege of visiting the district, and of collecting some of the platinum-bearing peridotite.

The Ural occurrence, both by reason of the presence of the platinum disseminated in basic igneous rocks and its connection with chromite and magnetite of acknowledged igneous origin, must be admitted to be a product of magmatic segregation; and how powerful this segregation has been we learn from the fact that assays of the ferrous blebs (the most basic segregations) in the Nizhni-Tagil rocks gave a figure corresponding to $50 per ton.†

That in this region the platinum has been remarkably concentrated, as compared with similar rocks in other places, is shown by the observation of Saytzeff that even rocks elsewhere not known to be platiniferous—"porphyrite, gabbro-diorite and syenite-gneiss"—contain it.‡

6. *Copper.*

Copper, as an original constituent, is known to enter into the composition of the dark ferro-magnesian silicates of the igneous rocks. It occurs also in meteorites, and, alloyed with

* C. W. Purington, "Platinum Deposits of the Tura River-System," *Trans.*, xxix, p. 8.

† Purington, *op. cit.*, p. 8.

‡ A note in the *Eng. and Min. Jour.*, November 16, 1901, p. 632, says that samples of rock from the State of Washington contain, according to Prof. J. F. Kemp, from 0.375 to 0.5 oz. of platinum per ton. The nature of the rock is not stated.

native iron, in the Ovifak (Greenland) basalt. The segregations of pyrrhotite before noted in connection with nickel, and believed to have formed in the distinctly ante-consolidation period, are frequently cupriferous, and even contain copper pyrites, as at Sudbury, Ontario. The magmatic segregation of the pyrrhotite being granted, the copper also has probably been chiefly concentrated in the same way.*

According to some observers, even high-grade copper-ores in various districts have had this origin.†

7. *Gold.*

Pyrrhotite frequently, and chalcopyrite generally, contains gold. Some masses of auriferous pyrrhotite and chalcopyrite have been thought to have originated like the niccoliferous pyrrhotite above mentioned. Such is the case at Rossland, B. C., where the ores have been considered by many writers to be magmatic segregations, while other observers, equally reliable, believe them to be secondary replacement deposits or fissure-veins. The hypothesis of a first concentration by magmatic segregation and a second by circulating waters may possibly be the key to the problem.

Native gold, probably as an original constituent, has been found in granite,‡ in eurite§ (alaskite), in quartz-trachyte,‖ and in gabbro.¶

IX. The Origin of Certain Gold-Quartz Veins.

As remarked in the preceding paragraph, native gold has been found in both basic and acid rocks. It has also been detected in the dark ferro-magnesian silicates of rocks of all degrees of acidity. The commercially-valuable concentrations of gold are generally connected, now with basalt or gabbro, now with diorite, now with phonolite, rhyolite, or granite. They occur also in many different forms, as replacement-de-

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* J. F. Kemp, *Ore-Deposits of the U. S. and Canada*, 4th ed., pp. 436–7.

† Vogt "Problems in the Geology of Ore-Deposits," *Trans.*, xxxi., p. 131. *Genesis of Ore-Deposits*, p. 642.

‡ G. P. Merrill, *Am. Jour. Sci.*, April, 1896, 4th series, vol. i., p. 309.

§ G. W. Card, *Records Geol. Surveys of N. S. W.*, 1895, p. 154.

‖ W. Möricke, *Tscherwak, Min. Mitth.*, xii., p. 195.

¶ Cited by J. F. Kemp, *Ore-Deposits of the United States and Canada*, 4th ed., p. 36.

posits in limestone; as disseminations in igneous and sedimentary rocks; as contact-deposits near intrusive masses; and in fissure-veins. Most of the known processes by which ore-deposits are formed have probably been active in producing gold-ores. A possible case of origin by segregation in a basic magma has just been noted (at Rossland). But the writer believes that most frequently the metal is concentrated in siliceous magmas.

After studying the Yukon gold-quartz veins in 1896–7, the writer announced a theory of their formation as the end-product of rock-segregation in the region where they occur.* In this connection a brief outline of the theory will be given, with a few additional observations, since made, which tend to strengthen it.

Under a previous heading, in considering the segregation (differentiation) of igneous rocks, the conclusion has been reached that many magmas segregate by a repeated concentration and consolidation of the basic constituents, leaving a more siliceous residue.

Just as this process may result in rocks of extreme basicity, such as olivine, hornblende and augite rocks, and even in segregated masses of the metallic minerals which ordinarily are accessory constituents, so, at the other end of the series, very siliceous rocks arise. From the siliceous granites the transition is gradual (and may often be observed in a single rock-mass) to more siliceous rocks, consisting almost entirely of quartz and alkali-feldspar without important admixture of the dark ferro-magnesian minerals.

These rocks are regarded by the writer as far more widespread and important than has generally been recognized, and to the group he has applied the general term "alaskite."† These alaskites may pass gradually into quartz-veins.

In the multitudinous and varied dike-rocks of Forty-Mile creek, Alaska, where most of the observations were made which led up to the theory in question, every stage in the increasing acidity was observed.‡ The rocks which here occur

* J. E. Spurr, "Geology of the Yukon Gold-District," 18*th Ann. Rept. U. S. Geol. Surv.*, Part III., p. 312.

† J. E. Spurr, "Classification of Igneous Rocks," *Am. Geologist*, April, 1900, p. 229.

‡ J. E. Spurr, "Geology of the Yukon Gold-District," 18*th Ann. Rept. U. S. Geol. Surv.*, Part III., p. 232.

in greatest bulk are hornblende granites and hornblende diorites, both of medium acidity. From these rocks the change is very gradual to the extremely basic rocks before mentioned. We will, however, not dwell on this phase of the segregation, but turn to the development of the siliceous rocks, which is equally well displayed.

The basic hornblende granite, which forms the greatest rock masses, contains subordinate quantities of biotite. By a very gradual transition the hornblende diminishes in amount as the proportion of biotite increases, so that the rock becomes a biotite-granite; and in many dikes the amount of biotite becomes less and less, giving rise to an extremely siliceous granite, in which the biotite is an insignificant constituent as compared with the quartz and feldspar. With further diminution of the biotite the granites change into essentially quartz-alkali feldspar-rocks—alaskites. These rocks are sometimes fine-grained, or may be coarse, like granites, but have a nearly uniform structure and composition. In the alaskite series the change is continued by a relative increase in amount of quartz and decrease of feldspar. One remarkable phase studied is a porphyritic dike-rock whose ground-mass consists almost entirely of quartz in small interlocking grains, giving, both in the hand-specimen and under the microscope, the exact appearance of a quartzite. Yet this rock contains scattered, but regularly distributed, porphyritic crystals of feldspar. It is thus not only related by the closest ties to similar slightly less siliceous alaskites of the same district, but it is only removed by its scattered porphyritic crystals from being a typical quartz-vein. Moreover, the superabundant quartz in these very siliceous dikes tends to segregate into bunches, which may become large, and which have all the characteristics of ordinary vein-quartz. With the progressive increase in silicification the quartz begins to occupy an important portion, and finally the larger portion, of the dike. The feldspar becomes restricted to certain places, sometimes occurring irregularly, sometimes collecting near the walls, while the quartz lies in the center.*

* This distribution is in accordance with the theory of segregation by the aid of convection-currents ("Yukon Gold-District," 18*th Ann. Rept. U. S. Geol. Surv.*, Part III., p. 306), by which the least siliceous and first-precipitated minerals are concentrated near the cooler dike-walls.

Finally, by the disappearance of the feldspar, the dike becomes an ordinary quartz-vein.

In one and the same dike the change from a coarse alaskite to a typical quartz-vein may be seen in all its stages.

The quartz-veins generally contain pyrites, as do all the other dikes of the region; they contain occasional biotite, and some segregated calcite, as do also the coarse alaskites. It may be remarked, in connection with the calcite, that epidote, the silicate of lime, aluminum and iron, is a constant and important mineral in all the rocks of the Forty-Mile region, from the hornblendites and pyroxenites to the most siliceous alaskites.

These veins contain pyrite, argentiferous galena and free gold. From them a portion of the Yukon placer-gold is probably derived, much of the remainder coming from older quartz-veins which, by reason of the shearing and metamorphosis they have undergone, do not offer plain evidence as to their origin.

Therefore it has been concluded that certain quartz-veins in the Yukon district (part, at least, of which are auriferous) have originated by a process of magmatic segregation, which has separated them from other materials while in a state of aqueo-igneous fusion (the condition of molten rock in general), and that they represent the siliceous extreme of that process. From this standpoint, they are a variety of the igneous rocks. But it has been shown that as magmas become more siliceous they also contain more water; so, when the stage of quartz-veins is reached, the magma is believed to be so attenuated that it may best be described as water highly heated and heavily charged with mineral matter in solution. There would thus be no great difference (save in their associations, and very likely in the selection of the mineral matters which they contain) between these solutions and others where the water may have had, say, an atmospheric origin; and a quartz-vein originating by magmatic segregation might often not be distinguishable from one formed in the many other ways which are possible. The main point of interest, so far as this discussion is concerned, is, as the writer believes, that veins originating by magmatic segregation are especially apt to contain gold (without the admixture of so great proportions of the commoner metals as is usual in ore-deposits), and that thus an important class of typical gold-quartz veins has been formed.

Having briefly stated the evidence and formulated the theory for the Yukon district, let us recite some of the evidence bearing on it elsewhere.

1. *Evidence as to the Origin of Quartz-Veins as Magmatic Segregations.*

Pegmatites are coarsely crystalline rocks which show close relationships with ordinary igneous rocks, such as granites, on the one hand, and with veins, such as are known to be due to precipitation from aqueous solution, on the other. Hence there has been much perplexity and contention, some referring them to the "igneous" rocks and calling them *dikes*, others insisting that they were "aqueous" and true *veins*. But the latest and best essays on the subject* agree that pegmatites are formed under conditions *intermediate* between those which govern the formation of siliceous "igneous" rocks like granite, and those under which quartz-veins are formed. There is, in short, no line of demarcation in nature, corresponding to our artificial and arbitrary one, between igneous rocks and certain aqueous veins—between granites and certain large masses of quartz.

Transitions of pegmatite- to quartz-veins, showing absolute and uniform gradation from one to the other, have been noted by Crosby and Fuller, Williams† and Van Hise,‡ and transitions or evident close and constant relations between pegmatites and granites have been noted by Crosby, Brögger, Van Hise and Williams.

Professor C. W. Hall§ has furnished notes on eastern and central Minnesota, where, in connection with intrusions of hornblende-biotite granite, are shown "granitic veins." These are "locally pegmatitic, with coarse and well-developed feldspar individuals imbedded in a matrix of hornblende and biotite, while elsewhere they are finely textured, possess a reddish

* "Origin of Pegmatite," by W. O. Crosby and M. L. Fuller, *Amer. Geologist*, vol. xix. (1897), p. 147; "*Die Mineralien der Syenit-pegmatitgänge der südnorwegischen Augit- und Nephelin-syenite*," by W. C. Brögger, *Zeitsch. für Kryst.*, vol. xvi., 1890, pp. 215–235. "Origin of the Maryland Pegmatites," by G. H. Williams, *15th Ann. Report U. S. Geol. Sur.*, 1895, p. 675. † *Op. cit.*, p. 679.

‡ *16th Ann. Report U. S. Geol. Sur.*, Part I., 1896, p. 688.

§ Keewatin Area of Eastern and Central Minnesota, *Bull. Geol. Soc. Amer.*, vol. xii., pp. 367–8–9 (1901).

color, and are highly siliceous in composition." Associated with these are veins of quartz. In the St. Louis river-district the veins, when wide, become pegmatitic. The veins sometimes carry segregated sulphides and siderite. One, on Kettle river, has been explored for gold.

Professor J. F. Kemp* observes that on the north shore of Long Island Sound "pegmatites are abundantly developed in connection with granites, and all grades are shown up to practically pure quartz." One of the largest quartz-veins, which Professor Kemp thinks belongs to the pegmatitic series, carries, in portions, ferruginous minerals and traces of gold.

Dr. E. Hussak† has described an auriferous quartz-vein in Brazil which he regards as an ultra-acid granitic dike. Mr. Waldemar Lindgren, however, dissents from this conclusion.‡

According to Phillips and Louis,§ at Timbarra, in New South Wales, "gold is found in granite; these gold-fields consist of a granitic tableland, traversed by dikes of eurite|| and pegmatite, also occasionally showing veins of auriferous quartz, which may possibly be segregation deposits."

At Silver Peak, Nevada, the writer noticed transitions from the granitic rock (which is there intrusive in Cambrian limestones) into quartz-veins. Mr. H. W. Turner, who studied this region more in detail, made the same observation independently, and communicated it subsequently to the writer. According to him, these segregated veins seem to be connected in some way with the Silver Peak ore-deposits, which are gold-quartz veins.

On the Mojave river, in Southern California, the writer observed one of the most rapid and complete transitions from quartz-veins into granite which he has ever seen. Here Paleozoic limestones and quartzites (considerably metamorphosed) are cut by intrusive granite, whose dikes grade into pegmatite, and these to quartz-veins. In a single dike he observed, within the length of not many yards, a complete transition from a

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* "The Rôle of the Igneous Rocks in the Formation of Veins," *Trans.*, xxxi., p. 182. *Genesis of Ore-Deposits*, p. 693.

† *Zeitschrift für prakt. Geologie*, 1898, p. 345.

‡ "Metasomatic Processes in Fissure-Veins," *Trans.*, xxx., 642, and *Genesis of Ore-Deposits*, p. 562.

§ *Ore-Deposits*, second edition, p. 649. || Alaskite.—J. E. S.

fine-grained pegmatite to a typical quartz-vein. Gold is found in this locality (Oro Grande), but, unfortunately, he did not remain long enough to find whether it is in these quartz-veins.

The writer has also studied the transition of granite and alaskite through pegmatitic stages to quartz-veins, in the Walker river range, in northwestern Nevada, near the Indian reservation; and again in the Mojave desert, southeast of Randeburg, California.

At Belmont, in Nevada, the writer has made a brief study of an interesting dike-rock and its associated phenomena.* The dike is one of the outlying offshoots from a large body of siliceous granite; it is nearly half a mile wide, and cuts Silurian slates and limestones. Near the contact the slates and limestones have been transformed into jasperoid† by the introduction of silica; in part they have also been altered to micaceous schists, often containing disseminated small bundles of yellow and red metallic oxides. In this rock occur quartz-veins which carry rich antimonial silver-ores.

The dike-rock varies greatly in texture and composition. One specimen collected, classed as a siliceous muscovite-biotite granite, is remarkable for the irregular arrangement of its constituent minerals, the quartz often segregating into bunches a quarter of an inch in diameter, with all the characteristics of vein-quartz. A coarser-grained biotite granite at some little distance has the same peculiarity, and in this place the blotches of quartz, mosaics of intergrown grains, are from one-third of an inch to one-half an inch in diameter. But the rock of chief interest is one which looks like a micaceous quartzite, and, indeed, consists essentially of muscovite and quartz. Microscopic study reveals it in the presence of the feldspar albite, and proves that the muscovite has largely been derived from the alteration of orthoclase. Yet the rock is fresh and hard, and the change has not been affected by surface weathering.

"The process must be regarded as one of endomorphism, and as connected and probably contemporaneous with the exomorphism indicated by the alteration of the siliceous limestone of the wall rocks to jasperoid and mica schist.

* J. E. Spurr, *Am. J. Sci.*, 4th series, vol. x., p. 351 (1900): "Quartz-Muscovite Rock from Belmont, Nev., the Equivalent of the Russian Beresite."

† J. E. Spurr, "Geology of Aspen District," Mon. xxxi., *U. S. G. S.*, p. 219.

"In both the intrusive and the intruded rock the result of the metamorphism has been the same, producing quartz and muscovite at the expense of the orthoclase on the one hand, and of the calcite and subordinate minerals on the other. In the case of the wall-rock the metamorphism, being apparently, from its distribution, dependent upon the intrusion, evidently took place after this intrusion, and was brought about by the solutions which accompanied the igneous rock, or were residual from its solidification. Within the dike the similar alteration was probably contemporaneous with that in the country-rock."*

White quartz-veins, often several feet in width, occur in the immediate vicinity of this intrusive mass. For these the conclusion is reached that:

"These quartz-veins are probably contemporaneous with those already described as occurring in irregular form within the dike-rock itself, and as evidently representing the final product of the residual solution of the general magma. In these quartz-veins† the metallic minerals [chiefly stetefeldtite, an argentiferous ore of antimony, with some lead, copper and iron] are scattered in branches or disseminated particles, rarely in banded form. . . .

"The metallic minerals being, from their habit, plainly contemporaneous with the quartz-veins which enclose them, it is evident that the deposition of these minerals, the formation of the quartz-veins, the metamorphism of the country-rock to jasperoid and muscovite schist, and the endomorphism of the muscovite-granite to quartz-muscovite rock were contemporaneous occurrences, all brought about by the same agencies, which were the solutions representing the end-product of the differentiation of the granitic intrusive rock."

This Belmont quartz-muscovite rock acquires additional interest as the equivalent of the so-called *beresite* of the Urals, which the writer has had the privilege of studying in the field. After considerable investigation and discussion, the Ural beresite (composed of quartz and muscovite) has been shown by Arzruni to be an alteration from a muscovite-granite in the same way as the Belmont rock. The analogy between the Belmont phenomena and those of Berezovsk is still more striking when we consider the close connection of the beresite with gold-quartz veins. This rock forms intrusive dikes from 2 to 40 meters wide, cutting schists. Previous to all scientific investigation, these dikes were recognized by the miners as the surest guides to gold. The auriferous veins are found in the dikes, and only rarely extend into the country-rock. They generally stretch across the dikes at right-angles to the walls, and have been considered as filling "fissures of contraction" by

* *Op. cit.*, p. 355.

† According to S. F. Emmons, "*Geol. Expl. of 40th Parallel*," vol. iii. (Mining Industry), p. 398.

Posepny.* This is probably correct, for the veins follow the same lines as the "columnar jointing" of dikes, which are due to contraction.

At Belmont the important point in determining the age of the quartz-veins is their contemporaneity with the contact-metamorphosis of the wall-rocks, which fixes their period of formation as during the final stage of the consolidation of the granite. We have not sufficient data to announce this same criterion for Berezovsk, and in the study of ore-deposits one must ever beware of reasoning too closely from analogy; but the fact that the "beresite" has, like the Belmont quartz-muscovite rock, originated not by surface alterations, but through deeper-seated solutions,† that this alteration seems a part of that which produced the gold-quartz veins,‡ and that the latter are confined to the dikes or their immediate vicinity,—all these are in favor of the hypothesis of the origin of the veins as the last and most siliceous and most fluid segregation product of the granitic magma.

2. *The Genetic Connection of Gold-Quartz Veins with Siliceous Igneous Rocks.*

We have reviewed a number of cases of the actually observed transition from siliceous igneous rocks to quartz-veins, with or without a pegmatic stage, and in most of these the veins contain disseminated metals, notably gold. When mining engineers and geologists begin to look more carefully for such transitions, it is probable that numerous others will be found. Meantime, the number of instances in which gold-quartz veins are intimately associated with siliceous intrusive rocks is really remarkable.

On the Pelly river, in British Columbia (a part of the Yukon gold-belt), Dr. G. M. Dawson§ found evidence to show that the development of quartz-veins had occurred contemporaneously with the upheaval of the granites, and probably by some action superinduced by the granite masses themselves while still in a formative condition.

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* *Genesis of Ore-Deposits*, first edition, p. 70; second edition, p. 76.

† The beresite is deeply decomposed by surface agencies, but this is independent of the agency by which the first rock originated.

‡ The beresite itself contains gold in small quantity (50 drachms to the ton).

§ *Ann. Rep. Geol. Nat. Hist. Survey*, Canada, vol. iii., Part I., p. 35 B.

In the Cook Inlet region, Alaska, gold is found in aplite* dikes, according to Mr. W. C. Mendenhall. In the Nome region, Messrs. Schrader and Brooks† report veins containing sulphides, quartz and calcite, cutting metamorphic marble and schists. A large area of granite is also reported.

In the Slocan District, British Columbia, according to W. A. Carlyle,‡ the typical gold-quartz veins, as well as quartz-veins carrying argentite, native silver and gold, appear to be confined to granite, while veins containing argentiferous galena, blende, siderite, tetrahedrite, etc., are found both in stratified rocks and granites. In California, Whitney§ noted that, while the granite itself is not metalliferous, its appearance seems to be closely associated with the metamorphism of the adjacent sedimentary rocks, while this latter condition is, as a general rule, the concomitant of the occurrence of minerals or metalliferous veins. Prof. J. F. Kemp‖ remarks: "The enormous introduction of silica is one of the most extraordinary features of the geology of the Sierras, and indicates a remarkable activity of circulating waters. The igneous intrusions doubtless promoted, if they did not cause, the circulations." In the Lake of the Woods district, schists, early granite, and gneiss are cut by later granite. The veins are found in the schists, but favor the portions near the contact with the granite or gneiss.¶

In the gold-bearing region of Nova Scotia, metamorphosed sedimentary rocks containing quartz-veins are cut by many great intrusions of granite.**

In Madison county, Montana, gold-quartz veins occur in granite; in Beaverhead county, at the contact between limestone and granite; in Lewis and Clarke county, in granite and slates, etc.††

In Rhode Island, quartz-veins are frequent around the great inclusions of granite. Traces of gold have been met.‡‡

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* "Alaskite."—J. E. S.

† *Trans.*, xxx., p. 238.

‡ Quoted by J. F. Kemp, *Ore-Deposits of the United States and Canada*, 4th ed., p. 395.

§ *The Auriferous Gravels of the Sierra Nevada*, p. 353.

‖ *Ore-Deposits of the United States and Canada*, 4th ed., p. 370.

¶ Kemp, *op cit.*, p. 385.

** Kemp, *op cit.*, p. 397.

†† Kemp, *op cit.*, p. 320.

‡‡ Kemp, *op cit.*, p. 383.

In the Appalachian gold-quartz region are numerous intrusions of granitic rocks, and pegmatite is abundant.*

In British Guiana, gold-quartz veins "occur mostly in metamorphic schists and gneiss; and nearly all the streams and rivers that traverse regions occupied by the above rocks, or by granite, are gold-bearing."†

In the Sutherland gold-fields in Scotland, the rocks are granites, gneiss, mica-schist, and quartzite, and, in a few localities only, quartz-veins. On the stream called the Kildonan, "the miners preferred working either in the vicinity of masses of granite, or in the neighborhood of a partially decomposed greenish schist."

No gold has been found *in situ* in this district, but the drift is entirely composed of fragments of purely local rocks, while quartz pebbles are almost entirely wanting.

Influenced by these and similar considerations, Messrs. Joass and Cameron are disposed to ascribe a granitic origin to the gold of this area.‡

On the island of Bömmel, in Norway, the chief country-rock is "gabbro," in which large dikes of "quartz-porphyry," passing into granite, and of altered diorite, occur; on the south of the district is a large tract of slate, in which are non-auriferous quartz-veins. The "quartz-porphyry" dikes, and those of diorite, contain strong gold-quartz veins, whose general contemporaneity with the period of igneous intrusion is shown by their being older than some dikes and younger than others.§

In the Kotchkar district, in the Urals, the gold-quartz veins, as seen by the writer on the occasion of a brief visit, are immediately the results of circulating waters subsequent to the consolidation of the country-rock; but they occur in, and are probably primarily dependent upon, the granite. There are analogies in many ways between this district and that of Monte Cristo, Washington State, U. S. A., where, according to the writer's study, the ore-deposits (chiefly replacements of igneous rocks by auriferous sulphides), while immediately the work of ordinary circulating waters, yet are closely dependent upon

* Phillips and Louis, *Ore-Deposits*, 2d ed., pp. 786–7.
† Phillips and Louis, *op cit.*, pp. 887, 888.
‡ Phillips and Louis, *op cit.*, p. 320.
§ Phillips and Louis, *op cit.*, p. 519.

great intrusive bodies of tonalite in which the *first concentration* has probably been effected by magmatic segregation.

In India, it has been stated by Mr. King that the so-called quartz-reefs of the Travancore State "are not really veins, but merely the outcrops of beds of quartzite, associated with feldspar, which run with the foliations of the gneiss. Although minute traces of gold may sometimes be detected in these rocks by assay, the amount present is far too small to render them of any commercial value as a source of that metal." The phrase "beds of quartzite, associated with feldspar," strongly suggests fine-grained siliceous alaskite dikes. In the Wynaad district, "the gold-bearing area consists of granite, gneiss, and various metamorphic rocks, traversed by veins of quartz, which, with their branches, are auriferous."*

In China, the reported gold-quartz veins occur almost entirely in granite, as at Ninghai, the Chao-Yuen district, and Yeshui in Mongolia.†

In Siberia, the connection of the gold with granite and granitite‡ has been observed in more than one place.§

Turning to Australia, we find a relation of the gold to siliceous igneous rocks quite as striking as in California and Alaska. In Victoria,

"Gold is not only found in veins traversing granite, felsite and diorite, but is also sometimes disseminated throughout the rocks themselves." ‖

I quote from Phillips and Louis:¶

"In a paper read before the Geological Society of London in April, 1872, Mr. Richard Daintree drew attention to the fact that the auriferous Devonian districts of Queensland are entirely confined to such as are penetrated by certain eruptive rocks, principally pyritous diorites. In these diorites, and near the point of their intersection with the Devonian strata, veins of quartz, calc-spar and iron-pyrites had been examined and found rich in gold, while the extensions of such veins at any considerable distance from the intrusive rocks were found to be barren. Instances were also adduced to show that the pyrites sporadically distributed through the diorites was occasionally distinctly auriferous, and had, by its decomposition and disintegration, produced drifts containing gold in paying quantities.

"In a subsequent communication, Mr. Daintree states that since the date of

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* Phillips and Louis, *Ore-Deposits*, pp. 562–3.

† Phillips and Louis, *op. cit.*, p. 618.

‡ "Alaskite."—J. E. S.

§ Quoted by DeLaunay, "Contribution à l'Études des Gîtes Métallifères," *Annales d. Mines*, August, 1897, 9th series, vol. xii., p. 224.

‖ Phillips and Louis, *Ore-Deposits*, p. 620.

¶ *Op. cit.*, p. 641–2.

his first paper he had learned from Mr. C. Wilkinson, then Government Geologist of New South Wales, that the same facts hold good for the New South Wales gold-fields lying in Upper Silurian or Devonian areas; and Mr. G. H. F. Ulrich, the Curator of the Technological Museum in Melbourne, in his catalogue of the rocks in that institution, gives details which go to show that the Upper Silurian rocks of Victoria owe their auriferous character to the same cause.

"He describes the diorites of Victoria as occurring mostly as dikes, varying in thickness from a few feet to several hundred, traversing Upper Silurian strata, and presenting nearly all the ordinary varieties of structure and composition of that rock. They are nearly always impregnated with auriferous pyrites, and are either traversed by or associated with quartz-veins. According to Mr. Ulrich, by far the greater proportion of the quartz-gold furnished by the gold-fields occupied by Upper Silurian rocks is derived from dikes of diorite. . . .

"The question as to when the auriferous pyrites was deposited in these diorites is of much interest, and one that it will be somewhat difficult to solve. It is, however, probable that in the majority of cases the pyrites was contemporaneous with the consolidation of the rock in which it occurs, although it is also possible that it may have occasionally owed its origin to the subsequent passage through the rock of metalliferous solutions. . . .

"Below the water-level, which usually very nearly coincides with the zone of decomposition, veins of a class which, on the whole, have proved very misleading to the miner, although often rich in gold, usually disappear. These follow the lines of jointing of the rock, and are probably due to the decomposition of auriferous pyrites and the re-deposition, from solution, of a portion of its material in local fissures. . . . Besides the veins above referred to, there are, associated with the intrusive auriferous rocks, others which Mr. Daintree considers as being of far greater practical importance, from being generally of greater width and more likely to be persistent in depth. *These he regards as the result of hydrothermal agencies which preceded and accompanied the protrusion,** and which in some cases continued long after the intrusive rock had cooled down."

Again, I quote the following:†

"Daintree, Hacket, Wilkinson and others have shown that a large portion of the gold in Victoria and Queensland is due to the agency of intrusive dikes of felstone, elvan and diorite, so that reefs of quartz in Silurian rocks are not, as was at one time supposed, the exclusive source of Australian gold.

"At Timbarra, gold is found in granite; these gold-fields consist of a granitic tableland, traversed by dikes of eurite‡ and pegmatite, also occasionally showing veins of auriferous quartz, *which may possibly be segregation deposits.*§ The weathered granite is sluiced, and very fine gold, to the extent at times of 5 dwt. to the ton, is obtained. *Gold has been found to occur here in unaltered granite, and in eurite,*‖ as well as in the decomposed granite."

In the Transvaal, in the Lydenburg district, a quartz-vein in a diorite dike was worked at Waterfall creek,¶ and at Ophir Hill is a silicified bed of dolomite, which has been—

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* The italics are mine.—J. E. S.

† *Op. cit.*, p. 649.

‡ "Alaskite."—J. E. S.

§ The italics are mine.—J. E. S.

‖ The italics are mine.—J. E. S.

¶ Phillips and Louis, *op. cit.*, pp. 734–5.

"mineralized by gold-bearing solutions, which are in some way connected genetically with the numerous dioritic dikes that traverse the district." In the De Kaap district the rocks, "both stratified and granitic, are traversed by dikes of diorite and pegmatite. . . . In the neighborhood of the granite, these rocks occasionally carry small ferruginous intercalated deposits, which are generally auriferous. . . ."

3. *The Subordinate Connection of Gold-Quartz Veins with Basic Igneous Rocks.*

To avoid misunderstanding, I wish to say here that I recognize the fact that gold-quartz veins may occur in or near basic intrusives, and may, indeed, be genetically dependent on them. In the Kolar gold-field in India, for example, the auriferous veins invariably occur in a band of "greenstone trap."* In Western Australia the veins are reported to occur chiefly in diorite and biabase.† But certainly an overwhelming majority of gold-quartz veins occur in connection with rocks of the dioritic and granitic families,—that is to say, with the two most siliceous families of the three which make up most igneous rocks; and of these granite-diorite rocks, the veins show a decided preference for the more siliceous groups, such as quartz-diorite (tonalite), granite and alaskite. On the other hand, the intimate genetic connection of these typical gold-quartz veins with distinctly basic rocks, such as those of the diabasic family, may be safely called exceptional.

Therefore, the statement may be formulated that *although gold is present in all igneous rocks, and may be unequally distributed in any of them, yet the conditions for concentration by magmatic segregation become more favorable in proportion as the rock becomes more siliceous, and become most favorable in what has been shown to be the extreme siliceous product of rock-differentiation—in quartz-veins and dikes.*

The explanation of this is a problem for future study.

X. Résumé of the Evidence Concerning the Preference of Certain Metals to Accumulate, by Magmatic Segregation, in Certain Rock-Types of the Established Classification.

I have already pointed out that if the rarer elements, which have been disregarded in establishing the classification of igne-

* Phillips and Louis, *op cit.*, p. 568. † Phillips and Louis, *op. cit.*, p. 700.

ous rocks, find themselves, as a result of magmatic segregation, more closely associated with certain of these rock-types than with others, it is not due to any merit in the classification, but because of the association of these elements with the commoner ones on which the classification is based. In proportion as this association is strong, the preference of a metal for a certain rock becomes more marked. These, then, are some of these preferences:

1. *Basic Rocks.*

Iron, as is well known, is most abundant in basic rocks, and iron-ore deposits formed directly by magmatic segregation are mostly confined to such rocks.

Chromium ore-deposits, due to magmatic segregation, are chiefly confined to the most basic rocks (peridotites) and their alteration products (chiefly serpentine).

Platinum also is characteristic of the most basic rocks (peridotites and serpentine).

Nickel is frequently closely associated, as the product of magmatic segregation, with iron, chromium and platinum, and is especially found in the most basic rocks.

Vanadium is chiefly found in basic rocks.*

Copper, on account of its easy mobility, occurs in many different rocks, and as the result of many varied processes. Yet it seems to be especially connected with, and at home in, basic rocks. De Launay says:† "Copper is geologically close to nickel, with which it is frequently met, notably in the peridotites of Canada, for, like nickel, it is, above all, a metal of the basic rocks. . . ."

2. *Siliceous Rocks.*

Molybdenum is chiefly found in connection with the siliceous igneous rocks.

Tin is seldom met with except in connection with granite.

Tungsten has practically the same associations as tin.

The rarer elements in general seldom occur in notable amount, except in pegmatites and granitic rocks.‡

* *Résumé* by J. F. Kemp, *Ore-Deposits of the United States and Canada*, 3d edition, p. 36.

† "Contribution à l'Étude des Gîtes Métallifères," *Annales des Mines*, August, 1897, 9th series, vol. xii., p. 191.

‡ Kemp, *Ore-Deposits of the United States and Canada*, 3d edition, p. 36.

Gold, as has just been argued, while a mobile metal and widely distributed, seems to show a preference for the siliceous igneous rocks.

XI. The Relation between Ore-Deposits Due to Magmatic Segregation and Other Ore-Deposits.

In nature there are no hard and fast lines. So we find that ore-deposits originating, as argued, by magmatic segregation, pass by transition stages into others whose characteristics demand a different interpretation.

Especially close is the connection between certain magmatic segregations, certain contact-deposits, and certain deposits of gaseous-aqueous (pneumato-hydatogenic) origin.

Magmatic segregations take place while the rock, as a whole, is yet liquid; they are due to the mobility of elements or crystallizing minerals in this liquid, and may be conveniently conceived as taking place through the action of convection-currents.

Upon the cooling of an igneous intrusive rock, however, what might be called a forced segregation takes place. As the rock becomes solid, those materials which are "left-over" are expelled, and find their way into the neighboring rock, or along the fissures of the igneous rock itself. These "left-over" materials consist chiefly of water, which is usually highly siliceous, and contains a great variety of other mineral matters in solution, and also, very commonly, an unusual quantity of gases. In these excretions the proportion of gaseous to liquid constituents appears to vary as widely as possible—dependent, probably, partly on the nature of the cooling-rock, partly on the conditions or rate of cooling, etc. According as the gaseous or the liquid elements preponderate, there result ore-deposits (for these expelled solutions often contain metals), which, from the internal evidence they offer as to their mode of formation, may be classed as pneumatogenic (pneumatolytic), pneumato-hydatogenic (gaseo-aqueous), or hydatogenic. To the first class belong the ores deposited by volcanic fumaroles, and the writer has referred the gold-ores of Mercur, Utah, to the same general division.* The second and third classes are

* J. E. Spurr, "Economic Geology of the Mercur Mining District," *16th Ann. Rept. U. S. Geol. Survey*, Part II., p. 452.

of great importance. To the second belong the tin-veins, and to the third the "contact-deposits" proper.*

The gold-quartz veins, such as have been considered to be formed by magmatic segregation, the veins of the tin-group, and the contact-deposits proper, are perfectly distinct in characteristics and origin; yet between the first and the second, and the second and the third, there are all transitions, indicating transitions in the conditions which produced them. In all three cases the mineralizing agents may be described as highly-heated water heavily charged with silica, and containing metals and other mineral matters, all being directly derived from an igneous rock in its last stages of consolidation from a molten condition. All are characteristic of the more siliceous intrusives. Tin-veins seem to be confined to granitic rocks; gold-quartz veins prefer granite, and after that diorite; while contact-deposits, like contact-metamorphism in general, are chiefly characteristic of the more siliceous rocks, granite or diorite. Yet the first may be conceived of as quietly segregating under pressure in a mobile though probably slowly congealing magma, the second as escaping from a cooling-rock into fissures or other channels, with relief of pressure and the consequent assumption of different form and proportion, and the third as also escaping from a cooling-rock, but under pressure and penetrating largely by capillary or osmotic action into the rock in contact with the igneous body. Each of these processes involves a different selection of elements by the solutions—hence tin-veins and gold-quartz veins are generally quite distinct.

Many pegmatites are closely related to tin-veins. They not infrequently contain cassiterite, and are characterized by fluorine and boron compounds, indicating gaseo-aqueous origin. Such pegmatites, like the true tin-veins, are not likely to contain gold, and cannot be taken as an indication of probable gold-quartz veins. On the other hand, pegmatites containing slight evidence of pneumatolytic origin may be closely related to and associated with gold-quartz veins. In some pegmatites gold has been found. But the quartz-veins that pass into relatively

* J. H. L. Vogt, "Problems in the Geology of Ore-Deposits," *Trans.*, xxxi., pp. 139, 140. *Genesis of Ore-Deposits*, pp. 650, 651. Waldemar Lindgren, "Character and Genesis of Certain Contact-Deposits," *Trans.*, xxxi., p. 226. *Genesis of Ore-Deposits*, p. 716.

fine-grained, highly siliceous igneous rocks, with slight display of coarse-grained pegmatite, have probably been formed under the most favorable conditions for the segregation of gold in them, *i.e.*, comparative freedom from the pneumatolytic actions which are so unusually important in forming the cassiterite veins. Yet the occasional presence of tin and its close associate, tungsten, as well as tourmaline, fluorite, etc., in gold-quartz veins shows that one set of conditions may pass gradually into the other. The occasional presence of tourmaline, fluorite, wolframite, tin, etc., in zones of contact-metamorphosis and in contact ore-deposits, contrary to the usual occurrence, is an illustration of the same principle.*

XII. The Sequence of Volcanic Eruptions Considered in Connection with the Sequence of Metalliferous Veins.

It has already been described how, in a certain volcanic field, the rocks erupted or intruded at different periods are of quite different character, and how dissimilar rocks may be most closely associated. Extremely acid and extremely basic rocks are often almost or quite contemporaneously intruded or erupted in the same locality. From this, and from the observed sequences, rough laws of succession have been deduced. These differ somewhat, according to the district in which observations were made in each case; but they practically agree in indicating that magmas tend to segregate into more basic and more acid (more and less siliceous) portions. The writer, following Professor J. P. Iddings, believes that an initial rock of intermediate composition ordinarily passes, by magmatic segregation, into rocks which are progressively more acid and more basic, till extremely siliceous and extremely basic varieties are obtained. According to this, if the rocks were regularly intruded or erupted at stated intervals, we might expect to find the law of segregation fully illustrated in the succession of rocks. Sometimes, indeed, this is the case; but very often the eruptions have taken place irregularly, so that the normal succession is hardly recognizable.

Prof. J. F. Kemp has called attention to cases of successive

* Compare J. H. L. Vogt, "Problems in the Geology of Ore-Deposits," *Trans.*, xxxi., p. 139. *Genesis of Ore-Deposits*, p. 650.

vein-formations of quite different characteristics in a single district, and has supported the idea that new intrusions of igneous rock, of a character different from the preceding intrusions (rather than new fractures, as has often been assumed), are responsible for the differences, the metals extracted from one igneous rock being different from those derived from another.* With this idea the writer is in general accord, and would add the suggestion that also the difference in the veins at different periods may often depend upon the progress of rock-segregation (differentiation) in a still unconsolidated magma, from which the metals, directly or indirectly, are derived. By applying the idea of the change of segregated metals with the progress of general rock-segregation, some light on mineral association and succession may possibly be obtained. For example, in many districts of the world gold and platinum are closely associated in placers. In these districts it is usual to find extremely acid and extremely basic rocks (complementary varieties) intimately associated, representing apparently an extreme stage of rock-segregation; and frequently, as in the Urals, the platinum is found to be derived from the basic rocks (peridotites), and the gold chiefly from gold-quartz veins in the siliceous ones (granite). This is one of the simplest cases. In an earlier stage of the rock-segregation, when the extreme rock-types had not originated, we would not find any platinum-segregations, and the occurrence of gold-quartz veins would be less probable. A similar example of mineral association, probably dependent upon rock-segregation, is the occurrence in the gold-quartz district of Forty-Mile creek, Alaska, of an ore containing nickel, iron, chromium and magnesia, and no gold.† Just as the gold-quartz veins here are intimately associated with the ultra-siliceous dikes, so this ore is probably connected with the ultra-basic ones; and, as the two sets of dikes have been considered complementary and due to a single process of segregation, the contrasted ore-formations must be considered in the same light.

In many districts it has been noted that the veins of different

* "Igneous Rocks in the Formation of Veins," *Trans.*, xxxi., p. 180. *Genesis of Ore-Deposits*, p. 691.

† J. E. Spurr, "Geology of the Yukon Gold-District," 18*th Ann. Rep. U. S. G. S.*, Part III., p. 295.

periods have different contents. Professor Kemp* has called attention to the San Juan region in Colorado, where the different veins have been classified by T. B. Comstock as follows: 1. The northwest system with tetrahedrite. 2. The east and west with bismuth, and less often nickel and molybdenum. 3. The northeast with tellurides and antimony, and sulphur-compounds of the precious metals.

The same writer cites, in this connection, the Telluride district in Colorado, where a heavy vein is cut out and faulted by a later one of different metalliferous character. He also recalls an occurrence near Freiberg, Saxony, where seven sets of veins have been recognized, distinct from one another mineralogically, and probably introduced at different periods. At Butte, Montana, there are two distinct sets of veins, one containing silver and no copper, and the other containing copper, silver and gold.

At Mercur, Utah, the writer has described two ore-bearing zones which are parallel and lie about 100 to 150 ft. from one another.† They are of different ages: The oldest, the "Silver Ledge," contains silver with only traces of gold, while the younger, the "Gold Ledge," contains gold to the exclusion of silver, together with cinnabar and realgar, minerals not found in the Silver Ledge.

This list might be amplified, but will serve to show the main features of the problem.

It is not safe or reasonable to refer such differences in veins to any one universal cause. In the Mercur case, the writer has reasoned that the Gold Ledge is essentially a pneumatogenic deposit, due to gases ascending along fissures; and that the Silver Ledge is a contact-deposit, due to waters *occluded* in cooling from the intrusive sheet of rhyolite porphyry at whose contact it occurs. In such cases the different nature of the mineralizing solutions is sufficient to produce entirely different combinations of vein-minerals derived from a single magma, although a change in this magma itself by segregation, or the

* "Igneous Rocks in the Formation of Veins," *Trans.*, xxxi., p. 179. Also, *Ore-Deposits of United States and Canada*, fourth edition, p. 288. *Genesis of Ore-Deposits*, p. 691.

† J. E. Spurr, "Economic Geology of the Mercur Mining District, Utah," 16th *Ann. Rep. U. S. Geol. Survey*, Part II., p. 403.

intrusion of a rock of a new kind is, of course, not improbable. In other cases the different character of rocks traversed by the same mineralizing solutions might operate to cause the precipitation in one rock of a different combination of minerals from that precipitated by another. Where, however, the different veins are in the same rock, and belong in the same category of ore-deposits (from the standpoint of the process of formation), the assumption of a change in the character of the igneous rock below, whether by new intrusions (mechanical change) or by segregation (chemical change), will probably be often justified. The fact that the different veins often occupy fractures of different trend and age is far from opposing this theory, for it is only by the aid of mechanical accidents like fracturing that new solutions can rise, and by their effects bear witness to the change that would otherwise not be known.

XIII. The Persistence of Petrographic Provinces, Considered in Connection with the Persistence of Metalliferous Provinces.

While an igneous rock of a certain kind is not necessarily limited to a certain part of the earth's surface, yet the rocks of a given district generally show marked and persistent differences, taken as a whole, from the rocks of other, even adjoining, regions. To these districts, showing within themselves, no matter how varied the rocks they contain, a certain "kinship" or "consanguinity" between the different rocks, the term *petrographic provinces* has been assigned.

For example, many of the rocks of northern Minnesota, especially the granites, show a constant excess of soda over potash, producing the variety soda-granite, which appears to be characteristic of this region.* Other regions have a large development of rocks especially high in the alkalies,—phonolites, nepheline-syenites, etc., rocks which in most regions are wanting. Rocks characterized by an especially great proportion of magnesia, such as peridotites, occur in certain regions and are wanting in others.

The differences which give rise to these petrographical provings are evidently due to the unequal distribution of the com-

* 21*st Ann. Rep. Minn. Geol. and Nat. Hist. Survey*, pp. 41, 42.

moner rock-forming elements, upon which rock-classification is based, in different portions of the earth's crust. In one region sodium is especially abundant, in another both sodium and potassium, in another magnesium, in another aluminum, etc. Some petrographic provinces show mineralogical differences which are wonderfully slight, considering their persistence—in one the granites may be chiefly hornblende granites, for example, and in another almost entirely biotite granites, owing to constant, slight differences in the proportions of aluminum, magnesium, calcium, potassium, etc., present in each. The existence of these petrographic provinces, characterized by different proportions of the commoner rock-forming elements, has been explained by extending the theory of rock-segregation or differentiation so as to make it applicable on a large scale, and by supposing that in great internal reservoirs (presumably connecting, or at least once connected) certain elements, by reason of their affinity, become more or less concentrated in certain portions. We are quite in the dark as to what might be a possible cause for this (as yet) hypothetical process, for certainly the theory of concentration by convection-currents on cooling has slight application here; but in science the apprehension of the fact very commonly runs ahead of the explanation, and this idea is at least a good working hypothesis, which has much to recommend it. By this theory all igneous rocks (in so far as they are not formed by fusion of sedimentary rocks or by mixing of already different magmas) have originated chiefly by segregation from an original universal magma.*

If one accepts as a working hypothesis (as the writer has done) this theory that the unequal distribution or the relative concentration of the commoner rock-forming elements in certain parts of the earth's crust (giving rise to distinct petrographic provinces and rock-types) has been effected by magmatic segregation, one cannot avoid accepting the same theory for the less common rock-forming elements.

If one accepts this for the distribution of sodium, potassium, aluminum, magnesium, titanium and phosphorus, he must accept it for manganese, barium, chromium, nickel, strontium, lithium, chlorine and fluorine; and if he applies it to these

* J. P. Iddings, "The Origin of Igneous Rocks," *Bull. Philosoph. Soc. Wash.*, vol. xii., p. 185.

latter, he must extend it to tin, bromine and cobalt; to lead, zinc, copper, arsenic, antimony, wolfram; to mercury, silver, bismuth, vanadium, tellurium and thorium; to gold and platinum, and even to iridium, ytterbium and germanium.*

Following this idea, and observing that some regions are especially rich in sodium, some in magnesium, and some in titanium (petrographic provinces), we should expect to find some especially rich in chromium, some in nickel, some in tin, some in lead, some in copper, some in mercury, some in gold, some in platinum, etc. This is well known to be the case, and these regions, characterized by special combinations or amounts of the rarer, especially the commercially-valuable, metals, I desire to call *metalliferous provinces.*

A metalliferous province does not necessarily coincide with a petrographic province, for the reason that I have already pointed out—namely, that the petrographic province and its contained rocks is classified solely on the basis of the commoner rock-forming elements; while the rarer ones, upon the distribution of certain of which *metalliferous provinces* may be distinguished, follow independent laws of segregation, which, nevertheless, may sometimes partly coincide with the laws of segregation of some of the commoner elements, by virtue of an affinity or preferential association between a rare element and a common one.

The helpfulness (to the investigator) and yet the final unreliability of these affinities will be at once seen upon consideration. Platinum, for example, is undeniably most abundant in basic rocks—peridotites; that is to say, it prefers the company of elements like magnesium, calcium or iron, and objects to that of silicon; yet all peridotites do not contain platinum, at least in equal amount. It is only in certain metalliferous provinces that platinum is sufficiently abundant in peridotites to become commercially interesting. The same remarks apply to chromium, nickel, etc. On the other hand, tin seems to prefer the society of silicon, and is always found in close connection with siliceous igneous rocks, chiefly granites; yet not all granites contain tin in notable quantities. The variation is

* For the relative proportion of the elements in the earth's crust, see F. W. Clarke, *Bull. U. S. G. S.* Nos. 78 and 148; also J. H. L. Vogt, "Ueber die relative Verbreitung der Elemente," *Zeitsch. für praktische Geol.*, 1898, p. 225.

enormous. So a study of the distribution of granite gives only a slight clue to the distribution of tin, and a knowledge of the occurrences of peridotite is only the first step toward a knowledge of the occurrences of chrome or nickel-deposits. This principle is of wide application. Igneous rocks have long been recognized as the ultimate sources of many, if not most, ore-deposits. Yet not all igneous rocks are connected with ore-deposits. One mass of diorite, for example, may be connected with rich ore-bodies (formed, it is needless to say, in most cases, finally through the concentrating action of circulating waters), while an exactly similar diorite in another region may have no ores at all associated with it. One may explain this by assuming that in the first-mentioned case there have been abundant circulating waters, especially heated ones, and plentiful faults, fractures and zones of weakness permitting the passage of these mineralizing agents; and that in the second case these conditions for concentrating the disseminated metals have not been so favorable. The writer recognizes these considerations as of vast and universal importance; and yet a comparison of regions equally favored with igneous intrusives, with abundant circulating waters, with the necessary channels for circulation and permeation, and with rocks favorable for the precipitation of the metals held in solution in the circulating waters (such as limestones, carbonaceous shales and porous sandstones), may show an utter difference in the amount and nature of the minerals concentrated. Moreover, the same type of rock—a diorite, for example—may be associated with chiefly silver-ores in one region, with copper in a second, and with gold in a third.

Detailed investigations concerning the less abundant metals in igneous rocks, although they have rendered the science of ore-deposits the inestimable service of proving the presence of these rarer elements, afford little ground for more extended conclusions, on account of their being so few and (necessarily, from the minute quantities dealt with) so inaccurate.

Yet it seems that they also corroborate the conclusion that the metals are very unevenly distributed.

Professor J. F. Kemp remarks:*

* "The Rôle of the Igneous Rocks in the Formation of Veins," *Trans.*, xxxi., p. 172; also, *Genesis of Ore-Deposits*, p. 684.

"Nevertheless, it is a fact of the greatest importance that the presence of the metals* in the igneous rocks has been established. Not all igneous rocks have yielded such results on assay. The general experience has been that when samples of several varieties have been collected in a given district, some have proved barren; and it must be admitted that some negative results have been obtained. As a rule, however, they are decidedly fewer than the positive results. It is likewise true that not all igneous districts contain veins of ore."

To this quotation the writer adds the suggestion that most of the assays made have been of igneous rocks in metalliferous districts, where we should *a priori* (according to the ideas previously set forth) expect a greater proportion of the metals; and that, if assays of rocks in non-metalliferous districts were made, the proportion of negative results might be decidedly in excess—although then, as now, the term "negative results" would probably only mean that the metals sought for were in quantities too small to be detected by chemical methods.

The chemical determinations of the presence of the more abundant of the relatively rare metals give results fully confirming the conclusions reached as to their unequal distribution in similar rocks. Nickel, for example, is recognized as especially at home in the most basic rocks—peridotites and pyroxenites; but Vogt† gives a table of nickel determinations in 32 rocks of this kind, which vary all the way from a trace to 0.6 per cent.

Petrographic provinces may be relatively small in extent, or they may be enormous. The writer has made a study of the volcanic region of the Great Basin,‡ where an area whose limits are not determined, but which extends as far east as Salt Lake, west into the Sierra Nevada, north into Idaho and Oregon, and south into California, shows the same types and the same general succession of Tertiary lavas. From later studies by the writer in the Monte Cristo mining district, Washington, it appears that the Tertiary eruptions here also correspond in types, age and general succession to those of Nevada;§ similar rocks, age and succession have been ob-

* Referring, of course, to the least abundant metals.—J. E. S.

† "Relative Verbreitung der Elemente," *Zeitsch. für prakt. Geol.*, July, 1898, p. 236.

‡ *Journal of Geol.*, vol. viii., p. 621.

§ See article by author on "The Ore-Deposits of Monte Cristo, Washington," *22d Ann. Rept. U. S. Geol. Survey*, Part II., pp. 711–865.

served on the Southern California coast;* and as far away as Mexico the studies of Ordoñez† have established the fact that the principal rocks, their succession and age, remain the same. Without being in danger of carrying this correlation to excess, I may point out that the Pliocene olivine-basalts of the Sierra Nevada‡ are abundantly present in Oregon and Washington; that the British Columbia basalts are approximately, at least, of the same period;§ and that throughout the whole of Alaska and into the Behring Sea occur olivine-basalts of Pliocene age.‖

Again, the abundance of basic andesites (typically augitic, often hypersthene-bearing, and verging towards basalts), all belonging to one epoch (very late Pliocene-Pleistocene), in a continuous belt in Alaska, running the whole length of the Aleutian Islands and peninsula, turning the same angle as the chief orographic and topographic features, and running down the coast past Sitka;¶ the occurrence of the same rocks, belonging to the same age, in Washington and Oregon (Mt. Rainier, etc.); the extension of the belt through the Sierra Nevada and along the western part of the Great Basin; finally its extension into Mexico,**—this is all striking, and deserves recognition. Moreover, this belt of late Pliocene-Pleistocene augite (hypersthene) andesites extends through Central and South America, in the Andes.†† In Alaska and in the Andes some of the cones of this epoch are still active; but the majority have become extinct.

It appears, then, that the whole extreme western part of the western hemisphere (the Pacific coast of the Americas) is a zone occupied by what (at some periods, at least) is and has been a single petrographic province.

It remains to be seen whether this province is not continued

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* I regret I have not at hand the paper of Mr. Smith in a recent *U. S. Geol. Survey Ann. Report*, in order to give an exact reference. (Santa Catalina Island.)

† "Las Rhyolitas de Mexico," *Boletin del Instituto Geologico de Mexico*, No. 14.

‡ J. E. Spurr, *Jour. Geol.*, vol. viii., No. 7, chart, p. 643.

§ G. M. Dawson, *Ann. Rep. Geol. Nat. Hist. Surv. Canada*, vol. iii., Part I., p. 37 B.; also, *Trans. Royal Soc. Canada*, vol. viii., Sec. 4, p. 15.

‖ J. E. Spurr, "Geology of the Yukon Gold-District," *18th Ann. Rep. U. S. Geol. Surv.*, Part III., p. 250.

¶ J. E. Spurr, "Reconnaissance in Southwestern Alaska," *20th Ann. Rep. U. S. Geol. Surv.*, Part VII., Map 13.

** Ezequiel Ordoñez, *op. cit.*, p. 66.

†† Zirkel, *Lehrbuch der Petrographie*, 2d edition, vol. ii., pp. 831–2.

into Asia with the change of orogenic trends in Alaska from northwest to southwest. The line of late Tertiary-Pleistocene volcanoes, which extends along the Aleutian Islands to Kamchatka, is represented by 15 or 20 cones in this peninsula; this line, following the general orogenic trend, runs southwest through the Kurile Islands, the Islands of Japan, and the Philippines, into the East Indies. Andesites—largely pyroxene andesites, and frequently hypersthene andesites—are characteristic of this chain also, as far as the famous volcano of Krakatua. This investigation might profitably be carried still further, but this is hardly the place for it.

Turning from these examples of petrographic provinces on enormous scales, we find that metalliferous provinces may also be of light extent, or may be exceedingly large. Taken broadly, they often coincide more or less roughly with petrographic provinces, just as these are apt to show some correspondence in their position and trends with zones of folding and fracture in the crust, with mountain ranges and the borders of continents. A metalliferous province which I have been studying somewhat lately is the rich chrome-bearing province of Turkey, which, with its center at the western coast of Asia Minor, extends across the Ægean Sea and includes Macedonia and eastern Greece, and in the other direction stretches over the western and southern portions of Asia Minor. This metalliferous province is connected with a petrographic province marked by ultra-basic igneous rocks and serpentines, with which the ore is associated; yet similar rocks are found in other regions, without the corresponding abundance of chrome.

Taking a larger example, compare, in North America, the Appalachian with the Cordilleran region. That there is a certain kinship among the ores of the Appalachian chain and its allied ranges has long been recognized by mining men. *It is recognized that the metals, though present, are constantly far less abundant than in the Cordilleran region.* Every now and then one hears of veins found in this region which give rich results on assay; but the discovery, though heralded in the newspapers, makes no disturbance in the mining world, for the mining man knows, from long experience with such discoveries, that the vein will directly "peter out." Gold-bearing veins

are pretty thoroughly scattered along this zone from Nova Scotia to Georgia; but the uncertainty and the relative poverty of these gold-deposits is proverbial.

Taking the western Cordilleras, on the other hand, we may remember that the California miners followed new finds northwestward, along the trends of the mountain ranges, into the Frazer river country, the Caribou district, the Omenica, the Cassiar, the Pelly, and the Yukon, until the slow progress has brought them to the neighborhood of the Behring Straits (the Nome district). It seems exceedingly probable, also, that this true "mineral zone" extends into Siberia. For I do not hesitate to call it a mineral zone, although the gold-quartz veins of the Yukon are far different in age from those of California. In fact, the existence of rich gold-ores along this zone, in deposits of various ages, and made under various conditions and in various rocks, only serves to emphasize the conclusion that this zone is essentially a metalliferous province, marked by a greater proportion of gold (considering the question of the gold alone) than the earth's crust in general.

Concerning metalliferous sub-provinces within the Cordilleras, I quote the following from Phillips and Louis,* not having access to the original authorities:

"Mr. R. W. Raymond,† in a paper on the mining districts of the United States, recalls the fact that W. P. Blake, in a note to his *Catalogue of California Minerals*, first pointed out that the mining districts of the Pacific slope are arranged in parallel zones, following the prevailing direction of the mountain ranges. More recently, Clarence King has summarized these phenomena nearly as follows: The Pacific coast ranges carry, on the west, quicksilver, tin and chrome iron-ores. The next belt is that of the Sierra Nevada and of the Cascade mountains of Oregon, which, upon their western slope, carry two distinct zones, a foot-hill chain of copper-mines, and a middle line of gold-deposits, which extend into Alaska. Lying to the east of this zone, along the eastern base of the Sierras, and stretching southward into Mexico, is a chain of silver-mines which are frequently included in volcanic rocks. Through Central Mexico, Arizona, Central Nevada and Middle Idaho there is another line of silver-mines which more often occur in the older rocks. Through New Mexico, Utah and Western Montana lies another zone of argentiferous galena lodes; and again, to the east, the New Mexico, Colorado, Wyoming and Montana gold-belt forms a well-defined and continuous chain of deposits. Raymond agrees that this parallelism exists, though in a somewhat irregular way, and that it is chiefly referable, as Blake and King have shown, to the structural features of the country."

This quotation the writer makes without deciding his belief

* *Ore-Deposits*, 2d ed., p. 740.

† *Trans.*, i., p. 33 (1873).

for or against the divisions as claimed. Undoubtedly the later discoveries within this region have been so varied as to make some of the distinctions doubtful; yet a careful consideration of the Cordilleran ore-deposits of western North America would probably result in the determination of definite metalliferous sub-provinces, which might or might not coincide with those specified. That Nevada, in general, is part of such a sub-province, characterized especially by the abundance of silver, with other minerals subordinate, is strikingly illustrated by the fact that the vigorous mining industry of this State, so exceedingly rich in ore-deposits, was permanently prostrated by the decline in the price of silver, while other regions, differing from this in the nature of their metallic wealth, have prospered.

XIV. Conclusion.

Our inquiries lead us to the hypothesis *that by magmatic segregation the metals of commercial value, as well as the other rock-forming elements, are irregularly and to a certain extent independently concentrated in certain portions of the earth's crust. Such portions, characterized by the relative abundance of certain metals, may be called metalliferous provinces.* It is in these provinces that ore-bodies will generally occur. The provinces may or may not be closely identified with petrographic provinces (divisions based on the relative abundance of the commoner metals and other elements), although, by reason of the chemical affinity which exists between certain of the rarer metals and certain of the commoner elements, they probably generally do so, to a certain extent at least. *Moreover, within these metalliferous provinces (as is the case within the petrographic provinces) magmatic segregation produces sub-provinces, secondary, perhaps, in theoretical importance to the grander divisions, but of more practical interest to miners.* To limit, again, the scope of our views, *by magmatic segregation the rarer metals (like the commoner elements, again) are in many cases preferentially concentrated into certain rocks in a given sub-province.* Finally, *within these rocks the metals may be segregated chiefly into certain portions, even producing, in the case of the commoner metals (iron, chromium, nickel, etc.), workable ore-deposits without further concentration; and, in the case of the less common ones, either directly producing workable deposits (certain gold-quartz veins, certain tin-veins, possibly certain platinum segregations—Urals—)*

or producing rocks relatively so rich that it requires only the concentrating action of other agents (chiefly circulating waters) to create "ore-bodies." It is the writer's belief that *the origin of metal-producing districts, as contrasted with barren districts, is in most cases due primarily to magmatic segregation, and that an important class of ore-deposits is due directly to this.*

Added to this initial process, there are the varied effects produced by gases and liquids occluded by cooling igneous rocks, and the enormous work of waters, surface and underground, which, by continued solution and deposition as well as by mechanical concentration, may, under favorable conditions, operate to bring the disseminated metals within smaller and smaller compass. Underground, these waters may be hot or cold; they may be ascending, descending, or moving laterally; they may transport their metallic load only a fraction of an inch, a few rods, or miles. Their final effect is to create *directly* what is, perhaps, the most important type of ore-deposits. The study of ore-deposits is a study in concentration—the concentration of some of the finely-disseminated rarer rock-forming elements into more or less compact masses. This concentration is effected chiefly by these processes: (1) magmatic concentration; (2) concentration by occluded gases and liquids from consolidating magmas; (3) concentration by the action of hot-spring waters (generally ascending); (4) concentration by the action of cold surface-waters penetrating underground (generally descending); and (5) concentration by the effects (chiefly mechanical, though largely chemical) of surface-waters at the surface.

Any one of these processes may be chiefly responsible for a given ore-body, but in many cases two, three or more of them may be important. Moreover, the history of an ore-deposit may comprise cycles, or repetitions of the same processes at different intervals, before the final concentration is sufficiently complete. Take, for example, the Nome beach-sands, where the gold is concentrated from the concentrates of older beach-sands, now transformed into land by a crustal uplift.*

On Napoleon creek, a branch of Forty-Mile creek, Alaska, there was found a strip of rich stream gold-placer ground in

* Schrader and Brooks, *Trans.*, xxx., p. 242.

a district where working was not otherwise profitable. The gold was apparently derived from a conglomerate of probable Cretaceous age which formed a belt crossing the stream at this point. The composition of the conglomerate showed that it was derived from the rocks and quartz-veins of the ancient (Algonkian?) gold-bearing series. In this ancient series, as already explained, the gold is believed to have been concentrated by magmatic segregation. Here, therefore, we have three distinct processes of concentration: (1) magmatic segregation (Algonkian?); (2) mechanical concentration by surface-waters (beach-sands—Cretaceous?); (3) mechanical concentration by surface-waters (stream-placers—Pleistocene). And it was only after the third process that the metal was sufficiently concentrated to become workable with profit—to become an ore-deposit, properly speaking.

Postscript.

Since the above was written, the writer has received the interesting paper of Mr. Luther Wagoner on "The Detection and Estimation of Small Quantities of Gold and Silver."* Mr. Wagoner gives a series of delicate assays of California rocks, remote from mineral deposits, for gold and silver.

Four specimens of granite gave respectively the following weights in milligrams per ton: Gold, 104, 137, 115, 1,130; silver, 7,660, 1,220, 940, 5,590. One specimen of syenite showed gold, 720; silver, 15,430. A sample of diabase contained gold, 76; silver, 7,440; and one of basalt, gold, 26; silver, 547. The sedimentary rocks tested were three specimens of sandstone from different localities, and two of marble (one of the latter from Italy). The sandstones gave respectively, in gold, 39, 24 and 21; in silver, 540, 450 and 320. The California marble showed gold, 5; silver, 212; the Italian sample, gold, 8.63; silver, 201. Several assays of San Francisco *bay-mud* (containing some organic material) gave gold from 45 to 125. Two assays of sea-water gave a mean of gold, 11.1; silver, 169.5.

These results are suggestive; and, although too few to base final conclusions on, the writer would like to call attention to some striking facts. On reckoning up the means of the results, we find that the granite averaged 371.5 gold and 3,852.5

* *Trans.*, xxxi., p. 798.

silver; the sandstone, 28 gold and 436.66 silver; the marble, 6.8 gold and 206.5 silver; and the bay-mud, 85 gold.

The relative proportion or the precious metals in the sedimentary and in the igneous rocks first claims attention. The mean of all the igneous rocks assayed in gold 329$\frac{5}{7}$, and silver 5,546$\frac{5}{7}$; of the sedimentary rocks (sandstones and marbles, not the bay-mud), 17.5 gold and 344.4 silver. That is to say, the mean of the igneous rocks assayed shows about 19 times as much gold and 16 times as much silver as the mean of the sedimentary rocks.

The relative proportion of the metals in the different sedimentary rocks is another point. The sandstones average four times as much gold and over twice as much silver as the marbles; while bay-mud (which on hardening would become shale) contains nearly 13 times as much gold as the marbles.

Take, next, the relative proportion of the metals in the different igneous rocks. We have in the list siliceous or acid rocks (granite and syenite) and basic rocks (diabase and basalt).

Diabase and basalt are, generally speaking, chemical and mineralogical equivalents, differing in their texture and structure. If we compare the average of the granites with that of the diabase-basalt, we find that the former is 371.5 gold and 3,852$\frac{1}{2}$ silver, while the latter is gold 51 and silver 4,008$\frac{1}{2}$; that is, the granites contain nearly 7.5 times as much gold as the diabase-basalt, but only about the same quantity of silver. If we add the syenite assay (probably unusually high) to those of the granites, and again compare the result with the diabase-basalt contents, we find that the acid rocks contain 9 times as much gold and 1.5 times as much silver as the basic ones.

In spite of the small quantity of data, these results are in accordance with the theoretical conclusions arrived at in this paper. One of these conclusions was concerning the higher content of precious metals in the igneous rocks as compared with the sedimentaries. A second conclusion was in regard to the relative concentration of the metals in the different sedimentaries—least in the limestones, which are *calcium* concentrations effected largely chemically from the sea-water through organic agencies; more abundant in the sandstones, which are *silica* concentrations, but effected mechanically and containing much *débris* from all sorts of rocks; and most

abundant in the bay-mud, which is a fine ground-up mixture of all rocks, and contains, besides, organic matter which is known to be a precipitant of metals from solution. A continuance of these experiments is highly desirable, to fix the point as to whether the order of richness in gold and silver of the sedimentary rocks is really 1, shales; 2, sandstones; 3, limestones.

Thirdly, as regards the igneous rocks, the uniformly superior gold content of the siliceous or acid rocks, as compared with the basic rocks, is noticeable. One must remark, also, that the same does not hold good for silver; for, although the basalt contains the least and the syenite the most, yet the diabase has a large amount. This, as far as it goes, is in accordance with the theory above advocated, that during the process of magmatic segregation the gold (*not* the silver) seeks the siliceous rocks by preference.

Discussion.

(*Trans.*, xxxiii., 1063.)

Alexander N. Winchell, Butte, Mont.: Mr. Spurr calls attention to the fact that an ore-deposit may be due to a succession of concentrations at different geological epochs. He cites an example of such a condition on Napoleon creek, a branch of Forty-Mile creek, Alaska.

It will perhaps be of interest to call attention to another example of the same general character, not so remotely situated. The example referred to is located on Pole creek, a tributary of Cherry creek, in the extreme northeastern part of Madison county, Montana. An excellent geological map of this region is to be found in the Three Forks folio (No. 24) of the United States Geological Survey. According to this map, Pole creek, in its upper course, occupies the contact between the "Flathead" formation, which Peale correlates with the Middle and Lower Cambrian, and an area of gneisses and schists supposed to represent the Archean. A visit to the region last summer enabled the writer to determine the presence of a thick conglomerate formation between the Flathead and the Archean. The conglomerate in question has an outcrop along the southwest side of Pole creek varying from one-half to one mile in

width; its maximum thickness in this region is at least 500 feet; lying conformably above it are 300 or 400 feet of schists, fine sands, etc. It may probably be correlated with the "Belt" formation of Peale, as it lies unconformably upon the schists and gneisses of the Archean, and is overlain (above the fine sands), apparently unconformably, by the Flathead formation. It seems to be auriferous throughout its extent, and somewhat richer at the immediate surface.

Let us outline, now, the successive concentrations of gold in this district. The igneous rocks of Madison county certainly belong to a "metalliferous province" rich in gold; but to consider that the province is due to segregation from an originally homogeneous magma seems to the writer to be straining the theory of differentiation considerably beyond the breaking-point. As pointed out by Fouqué,* we have no evidence that such a primitively homogeneous magma ever existed; on the contrary, the marked heterogeneity of meteorites argues that cosmic materials are far from homogeneous.

Omitting, then, from the series, Spurr's concentration by magmatic segregation, which in this case one would probably have to refer to Archean time, we have: (1) mechanical concentration by surface-waters (ocean conglomerates and gravels —probably pre-Cambrian); (2) residual concentration by surface-waters due to disintegration and erosion; and (3) mechanical concentration by surface-waters producing stream placer-deposits.

It seems just possible that the same conglomerate caps the so-called "Gravel Range" about the head-waters of Alder creek (about thirty miles distant as the crow flies), in which case it probably aided in the formation of the famous Alder Gulch placer-deposits.

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* *Bull. Soc. Fr. Mineral.*, 1902, xxv., p. 349.

No. 12.

The Chemistry of Ore-Deposition.

BY WALTER P. JENNEY, E.M., PH.D., SALT LAKE CITY, UTAH.

(New Haven Meeting, October, 1902. *Trans.*, xxxiii., 445.)

CONTENTS.

I. The Reducing Action of Carbon and of Hydrocarbons, . . . 305
II. Protective Action of Carbon and of Hydrocarbons, ... 311
III. Contributory Action of Carbonic Acid Gas, ... 312
IV. The Stability of Carbonic Acid and of Water, ... 313
V. Occurrence of Carbon and the Carbon-Compounds, ... 315
VI. The Occurrence of Carbon, Alone, ... 315
VII. The Occurrence of Carbon Combined with Hydrogen, . . . 320
VIII. The Relative Reducing Power of Minerals, ... 347

I. The Reducing Action of Carbon and of Hydrocarbons.

Carbon has long been recognized as one of the most powerful reducing agents in the deposition of ores. Investigations, made by myself, of the zinc- and lead-deposits in Southwest Missouri, in the region centering about Joplin, where the formation of the metallic sulphides has been due to the action of bitumen, carbonaceous shales and bituminous coal, have afforded abundant evidence that the solid oxygenated hydrocarbons, particularly when in fine powder and in suspension in the waters circulating through the ore-bodies, are the most energetic and powerful reducing agents known.

Bitumen, liberated by the decomposition of the ore-bearing limestone, is found in the Joplin mines in all degrees of fluidity and hardness, dependent on the amount of oxidation it has undergone. From semi-fluid maltha it grades into partly oxidized mineral-pitch, which, by further oxidation, changes to hard asphalt, finally breaking up, from continued absorption of oxygen, into a fine powder resembling in appearance powdered coal. In this condition oxidized bitumen, from its light gravity, is transported readily in suspension in the underground circulating-waters.

Bituminous coal and black carbonaceous clays and shales occur as surface formations, often in intimate association with

the ore-deposits, and when broken up, crushed, and faulted by crustal movements, furnish organic matter in a state of fine division. This is borne by the surface-waters and redeposited, often in large masses, in the channels and spaces in the ore-bodies.

Apparently the only pure form of carbon occurring in the ore-deposits of the Joplin region is the charcoal, which is found in inconsiderable quantity in the bituminous coal; all other carbon is combined with hydrogen, oxygen and nitrogen.

All these hydrocarbons readily absorb oxygen from the air contained in the subaërial waters, and undergo at ordinary temperatures, even below ground-water level, a slow combustion, the ultimate product being carbonic acid and water. They deoxidize the circulating waters by consuming all the free oxygen; and they reduce to sulphides any sulphates that may be in solution. Even ferrous and ferric sulphates, on coming in contact, in solution, with any of the solid hydrocarbons, are at once re-formed as pyrite or marcasite,—minerals that reduce all other metallic sulphates, first, by being oxidized to ferrous sulphate, and then, by further absorption of oxygen, to ferric sulphate and limonite.

Bain, writing of these mines, says, "The widespread presence of bitumen has been already emphasized. The ground-water is one great reducing solution."* Nearly every observer in this field has recorded the association of bitumen with the zinc- and lead-ores.

In my paper on "The Lead- and Zinc-Deposits of the Mississippi Valley"† I called attention to the reducing action of bitumen and bituminous shales in the formation of the ore-deposits of the Joplin District, and noted the influence of organic matter in the rocks upon the selective deposition of the ores in certain beds in the Cambrian and Silurian of Central and Southeastern Missouri, and also of the Upper Mississippi lead-region.

In limestones containing organic matter, especially if the rock be easily dissolved by waters carrying carbonic acid, the efficiency of even so minute a quantity as a fraction of one per

* *The Lead- and Zinc-Deposits of the Ozark Region*, by H. F. Bain, p. 159.

† *Trans.*, xxii., 171-225.

cent. of bituminous substances, in inducing the precipitation and crystallization of the ores, is very great. Small as the proportion of the carbonaceous matter may be, it is liberated by the rapid subterraneous erosion of the lime-strata, in quantity more than is required to consume the free oxygen in the ore-forming solutions, and to reduce all sulphates to sulphides. In limestones highly soluble in carbonated waters, two-tenths of one per cent. of any strongly deoxidizing material, as bituminous coal or bitumen, disseminated in the rock, appears to be ample to effect the reduction of the metals, and to induce the deposition of the ores in the special geological formation.

Compared with carbon, hydrogen has far greater reducing power, measured by the amount of oxygen consumed, for hydrogen, in the production of water, combines with three times the weight of oxygen that unites with carbon in forming carbonic acid. In fact, hydrogen stands first in reducing power, accomplishing nearly nine times the work of pyrite, the most efficient metallic sulphide in the redeposition of ores. Sulphur, oxidizing to sulphuric acid (SO_3), requires less than one-fifth the oxygen that combines with an equal weight of hydrogen in forming water.

For illustration, the relative reducing power of hydrogen, carbon and sulphur may be compared with the heat generated by their combustion, although their calorific values do not run parallel with their respective powers in the deoxidation of mineral solutions.

A calory being the quantity of heat necessary to raise 1 lb. avoirdupois of water 1° C., the heat generated by the combustion of 1 lb. of the following substances is:

	Calories.
Hydrogen,	34,462
Carbon,	8,140
Bituminous coal,	8,750 to 7,800
Lignite,	7,300 to 4,600
Sulphur,	2,250

On account of the calorific value of the contained hydrogen, the heating-power of the highest grade of bituminous coals is greater than that of pure carbon.

It is not improbable that the bituminous coals occurring in association with the ore-deposits of the Southwest, on account of their purity and high percentage of hydrogen, have a some-

what greater reducing power than pure carbon, and are exceeded in power and intensity of action only by bitumen. The lignitic or finely divided coaly matter, disseminated in the black clays and shales, may be regarded for the purpose of this discussion as a form of highly impure bituminous coal. Anthracite may be classed with the bituminous coals, as it contains from 1 to 3 per cent. of hydrogen and 1 to 3.5 per cent. of oxygen.

The hydrocarbons may be divided into the petroleums, or fluid non-oxygenated compounds of carbon and hydrogen; the bitumens and asphalts, solid oxidized hydrocarbons, soluble in chloroform or other solvents of the resins; and the pyro-bitumens, which also contain oxygen and nitrogen, including anthracite, bituminous coal, lignite, etc.

The Oxygenation of Petroleum.

Experiments made by the author on the oxidation of petroleum show that the heavy hydrocarbon oils unite very slowly with oxygen, when first exposed to its action, even at temperatures as high as 150° C.; but after the action is once started, by the combination of even a little oxygen with the hydrocarbon, the further oxidation then proceeds with constantly increasing energy. By aspirating a current of air for ten days through heavy petroleum oil, at 140° to 155° C., there were formed solid hydrocarbons, resembling certain natural asphalts. Very little water was formed; the oil "cracking" and the hydrogen being removed in the form of light naphthas and non-condensable gases, containing a greater percentage of hydrogen than the original oil, and leaving oxidized hydrocarbons, with less hydrogen and a greater proportion of carbon.* The asphalts made in the above experiments absorbed oxygen from the air at ordinary temperatures; the rapidity of the absorption being increased if the asphalt was in a fine powder. Dana refers to these results as the manufacture of grahamite from petroleum.†

The oxides of lead, zinc and manganese, and certain salts of

* "On the Formation of Solid Oxidized Hydrocarbons Resembling Natural Asphalts by the Action of Air on Refined Petroleum," by W. P. Jenney, *American Chemist*, vol. v. (April, 1875), pp. 359–362.

† *System of Mineralogy*, edition of 1898, p. 1020.

the metals, notably manganese-borate, are powerful driers of the vegetable oils, such as linseed oil. Even in solution, many salts of the metals have a drying action if agitated with the oil. In the case of the vegetable oils, these metallic oxides and salts appear to exert a catalytic action in accelerating the combination of oxygen with the hydrocarbon.*

Experiments by the writer indicate that oxides of lead and manganese have a similar action in promoting the union of oxygen with petroleum; and that the asphalts produced retain 2 per cent. or more of lead-oxide, even after treatment with boiling acetic acid and purification by solution in chloroform or ether.†

From this point of view, it is probable that the oxidation of bitumen, in effecting the re-formation of the sulphides, is accelerated, and the intensity of the reducing action increased, by the catalytic influence of ferrous and ferric sulphates and by the various sulphates, carbonates, chlorides and oxides of lead, zinc, copper and manganese, which are always present in greater or less amount in the ore-deposits. With petroleum having a paraffin base, the union with oxygen would be extremely slow, were not the chemical activity stimulated in some way. Petroleum with an asphalt base, owing to the heavy hydrocarbons in the oil being combined with oxygen, and approaching fluid bitumen or maltha in composition, would probably absorb oxygen more rapidly.

That the natural asphalts and bitumens, when wet, are more subject to the action of oxygen than when dry, has been observed in the wear of asphalt pavements, which rapidly disintegrate in spots where surface-water accumulates.

The Chemical Reactions that Take Place.

In the reduction of metallic sulphates to sulphides, by carbon, the action in each case is deoxidation, with formation of carbonic acid, according to the following reactions:

$$ZnSO_4 + 2H_2O + 2C = ZnS + 2H_2CO_3.$$

$$PbSO_4 + 2H_2O + 2C = PbS + 2H_2CO_3.$$

* Catalytic action is understood to be the action of a substance which, by its presence, accelerates or retards the chemical activity, and may induce a chemical reaction that would otherwise not occur, or would take place only with extreme slowness.

† *Op. cit.*, pp. 359-362.

The complete reduction of ferrous sulphate to pyrite or to marcasite requires that free sulphuric acid be present:

$$2FeSO_4 + 2H_2SO_4 + 5H_2O + 7C = 2FeS_2 + 7H_2CO_3.$$

The carbonates of lead, zinc and iron, in the presence of alkaline sulphates, are reduced by carbon to the corresponding sulphides, galena, blende and pyrite:

$$PbCO_3 + Na_2SO_4 + 2H_2O + 2C = PbS + Na_2CO_3 + 2H_2CO_3.$$

$$ZnCO_3 + CaSO_4 + 2H_2O + 2C = ZnS + CaCO_3 + 2H_2CO_3.$$

$$2FeCO_3 + 4CaSO_4 + 5H_2O + 7C = 2FeS_2 + 4CaCO_3 + 5H_2CO_3.$$

Chalcopyrite, $CuFeS_2$, is formed by the double reduction of cupric sulphate and ferrous sulphate:

$$CuSO_4 + FeSO_4 + 4H_2O + 4C = CuFeS_2 + 4H_2CO_3.$$

The reactions which take place where the hydrocarbons form the reducing agents are more complex. The hydrocarbons at first lose hydrogen and gain oxygen, until disintegration occurs; then they rapidly oxidize to carbonic acid and water. With bitumen and coal, it is probable that practically all the carbon is finally converted into carbonic acid, and the hydrogen into water. In the oxidation of petroleum some "cracking" may occur, and a portion of the hydrogen and carbon may escape in the form of light hydrocarbon gases, as did take place in the experiments described above.*

Oxygen seems to be needed to complete the reaction in the reduction by petroleum of the paraffin series:

$$12ZnSO_4 + C_{16}H_{34} + O = 12ZnS + 16H_2CO_3 + H_2O.$$

Where the petroleum is partly oxidized, ferric sulphate forms pyrite in the presence of an excess of free sulphuric acid. The reaction may be written as follows:

$$3Fe_2(SO_4)_3 + 3H_2SO_4 + C_{16}H_{30}O_2 = 6FeS_2 + 16H_2CO_3 + 2H_2O.$$

To illustrate the partial reduction of ferric sulphate to pyrite,

* See p. 308.

with formation of ferrous sulphate, the formula of an oxidized hydrocarbon nearly corresponding to humus acid is assumed, as in the following equation:

$$4Fe_2(SO_4)_3 + 8H_2O + C_{16}H_{16}O_8 = 4FeS_2 + 4FeSO_4 + 16H_2CO_3.$$

The complete reduction of ferrous sulphate to pyrite or to marcasite by an oxygenated hydrocarbon, such as gilsonite, $C_{13}H_{20}O$, also requires the presence of free sulphuric acid:

$$5FeSO_4 + C_{13}H_{20}O + 5H_2SO_4 + 3H_2O = 5FeS_2 + 13H_2CO_3 + 5H_2O.$$

II. Protective Action of Carbon and of Hydrocarbons.

Hydrogen and carbon have affinities for oxygen stronger than those of any other chemical elements, under conditions normally occurring in ore-bodies. By consuming the free oxygen in the circulating-waters, they act to preserve and shield from decomposition all metallic sulphides. Otherwise stated, all forms of carbon, and of the fluid and the solid hydrocarbons, when present in excess, owing to their superior affinity for oxygen, prevent the oxidation of the ores; although many of the minerals in the ore-bodies under other conditions, where carbon and its compounds are absent, or present only in a subordinate degree, are powerful deoxidizing agents.

In the mines at Joplin, Mo., the metallic sulphide-ores, blende and galena, and the associated minerals, chalcopyrite, pyrite, and even marcasite, are protected from decomposition below ground-water level by the bitumen and the bituminous shale contained in the wall-rock and present in the ore-bodies. Near water-level, on the boundary between the zones of oxidation and reduction, these hydrocarbons are consumed in places; although, a few feet distant in the same ore-body, they may occur in great excess. In such places the metallic sulphides undergo oxidation, only to be re-formed anew on coming in contact with the hydrocarbon.

This protective action has long been understood with respect to the rocks which contain organic matter. In the black-band iron-ores, and in many bituminous shales, the iron occurs as the proto-carbonate (siderite), and is preserved from oxidation by

the hydrocarbon. In the outcrop, such rocks are bleached by weathering, and the iron is oxidized to limonite or hematite. That organic matter preserves the strata from oxidation is a fact familiar to persons engaged in collecting fossils, particularly fossil-plants. The beds of black and gray shales, where the iron occurs as carbonate or sulphide, are carefully searched, while bright-colored strata, in which the iron is peroxidized, are given only a slight examination.

III. Contributory Action of Carbonic Acid Gas.

In the formation of ore-deposits, carbonic acid gas may, under special conditions, displace and expel the air from the cavities, channels and interspaces in the rocks, and in this way, by mechanically excluding the air, materially aid the reduction and precipitation of the ores by the ordinary deoxidizing agents. Conditions also occur in the oxidation and re-formation of an ore-body, particularly at those points where the zones of oxidation and reduction merge one into the other, under which carbon dioxide would be an efficient auxiliary in the process of reduction.

The specific gravity of carbonic acid gas, compared with air as the standard, is 1.524. Its action in displacing air is not unlike that of water; a rise in the ground-water from any cause, as is often observed, drives out the air from all the openings in the ore-bodies and checks the oxidation of the minerals.

In the Parker mine, Wood River, Idaho, the country-rock is a lime shale, heavily charged with graphite. Above the permanent water-level all the seams and joints in the rock are filled with carbonic acid gas, produced by the oxidation of the carbon. Carbon dioxide is found in a zone reaching from ground-water level to within 100 ft. of the surface; in this zone it fills all the rock-openings as perfectly as water fills similar openings below.*

Sulphuretted hydrogen gas, which has a specific gravity of 1.19, may act in much the same manner in excluding the air, although in itself it is a strong precipitating and reducing agent.

* See pages 319 and 320.

Natural gas, notwithstanding its low specific gravity (0.558), may be held under pressure in the strata in much the same way as it occurs sealed in the interspaces of the Trenton limestone of the Ohio and Indiana gas-field.

At the Silver-Islet mine, Lake Superior, pockets filled with hydrocarbon gas were struck in drifting on the vein on the 8th (440 ft. vertical depth) and 10th levels (610 ft. depth). The gas was held confined in the seams of the slate and in the openings in the vein under a water-pressure of from 440 to 600 ft., equal to a pressure of from 190 to 265 lbs. per square inch.*

Observations at many gas-wells show that the pressure greatly exceeds that which would be due to a water-column equal in height to the depth of the gas-producing strata. There is no record of any measurement of the gas-pressure at Silver-Islet.

IV. The Stability of Carbonic Acid and of Water.

Carbonic acid when combined with a base is a weak acid, readily displaced by a stronger, as sulphuric, hydrochloric or phosphoric acid, and also by sulphur and by many of the organic acids. But the molecule of carbonic acid is never broken up, is never separated into its component elements under conditions ordinarily subsisting in the earth's crust, at least not at the depths reached in the underground circulation of meteoric water.

Volcanic action alone, or an earth-temperature far above normal, furnishes the physical conditions in which carbon dioxide is dissociated, or the conditions that admit of its being reduced to the monoxide by carbon, or by other deoxidizing agents.

Carbonic acid is a permanent refuge of oxygen; once locked up in combination with carbon, oxygen remains inert for all time, in a condition of stable equilibrium, inactive, and chemically indifferent to all the complex changes taking place in the depths of the earth.† Even in ore-deposits undergoing oxida-

* "The Silver-Islet Mine and Its Present Development," by Francis A. Lowe, *Eng. and Min. Jour.*, vol. xxxiv., pp. 320–323. See, also, p. 346, this paper. "Silver-Islet Mine, Lake Superior" (author unknown, with Supplement No. 1, by W. M. Courtis), *Eng. and Min. Jour.*, vol. xxvi., p. 438.

† Carbonic acid gas contains: Carbon, 27.27 per cent.; oxygen, 72.73 per cent.

tion and re-formation, carbonic acid, once formed, is itself insusceptible to chemical change. Neither hydrogen, carbon, sulphur, or the most powerful deoxidizing metallic sulphides, can decompose it at ordinary temperatures. This immutability, however, is maintained only under the conditions subsisting in the depths of the strata, where life does not exist; the carbonic acid in the soil and in the atmosphere readily gives up its oxygen and carbon to plant-life.

Water almost equals carbonic acid in stability. It is true that water is decomposed by electrolysis and in many chemical reactions in the laboratory; yet, at temperatures approaching the normal, water is probably not dissociated, except in a very limited way, in any of the processes incidental to ore-formation.

In the complex chemical changes that take place in the oxidation and re-formation of ores, it is possible that water may be decomposed; but, quantitatively, such dissociation must be insignificant. Practically, water may be regarded as chemically stable under ordinary conditions and temperatures. The fact that, in the presence of the deep-circulating underground waters that contain no free oxygen, the complex sulphides forming the ore-bodies have been preserved unaltered for ages, is evidence that water is chemically inert to all the elements present in the depths of the strata.

Among minerals, many oxygen compounds, as, for example, quartz, corundum, cassiterite, rutile and zircon, resist decomposition, as do also the silica, the alumina and the other acid radicals in silicates, aluminates, borates, phosphates, titanates, tantalates, tungstates and chromates. Minerals containing oxides of the alkalies and the alkaline earths, while usually permanent, may have their oxygen displaced by sulphur and by the halogens, chlorine, bromine, iodine and fluorine. In the greater number of the refractory minerals and permanent oxygen-compounds, the chemical union of the elements with oxygen may probably date back to the primal origin of the earth.

Carbon and hydrogen alone, of all the elements, unite with oxygen under conditions now subsisting in ore-deposits, to form fixed compounds, that, sealed in the rocks, can endure to the end of time.

V. Occurrence of Carbon and the Carbon-Compounds.

Carbon occurs as graphite in the metamorphic rocks and in the gangue of certain mineral-veins. It is also found, practically free from hydrogen, as graphitic anthracite, and, in small quantities, as native charcoal. In all cases carbon is the residual element in the decomposition of the organic matter deposited in the original sediments; the hydrogen, oxygen, nitrogen and sulphur with which it may have been combined have been eliminated.

Far more commonly, carbon, when in association with mineral-deposits, is combined with hydrogen and oxygen, usually in the form of bituminous coal or bitumen in the wall-rocks, or filling the ore-bearing fissures; in some instances, as in the Joplin, Mo., mines, it is distributed generally throughout the ore-bodies. In most carbonaceous shales, in the mining regions, the organic matter is mainly in the form of finely disseminated bituminous coal.*

It is somewhat remarkable, considering the almost universal distribution of petroleum, that the non-oxygenated hydrocarbon oils are found so seldom, either in the ore-deposits or in the ore-bearing formations. In a few instances, marsh-gas and other similar hydrocarbons which are gases at ordinary temperatures and pressures have been found in association with mineral-deposits.

VI. The Occurrence of Carbon, Alone.

Graphite.

In the metamorphic area of the Black Hills of South Dakota many large, irregular deposits of pyrrhotite occur, associated with belts of graphitic shales. Masses of crystalline pyrrhotite are encased in soft, black, shaly gangue-rock, carrying a large percentage of graphite. As observed by the author, these graphitic shales appear to form a specially favorable gangue for pyrrhotite, associated with ores of nickel and copper, and also for pyrite and arsenopyrite.

* An analysis of the Hudson-River slates (Lower Silurian) gave 5 per cent. of fixed carbon and 3 per cent. of volatile combustible matter, or nearly in the proportion of carbon, 62.5 per cent.; volatile, 37.5 per cent.; corresponding to the composition of the best gas-coals. "Classification of Coals," by Persifor Frazer, Jr., *Trans.*, vi., 448.

Pyrrhotite is mined in the vicinity of Deadwood, S. D., for flux in pyritic smelting. The mineral shows on assay an average value of $1.00 to $2.00 per ton in gold, with usually less than 0.25 per cent. of copper. Many of the deposits of pyrrhotite in the region lying easterly and northeasterly from Harney's Peak carry a small percentage of nickel and copper. Dr. Carpenter says that assays of the nickeliferous pyrrhotite from this region, made at the Dakota School of Mines, show an average of 1.5 per cent. nickel, though samples carrying 8 per cent. have been found.*

F. M. F. Cazin describes the occurrence, in the Vermont copper-mine, of deposits of the sulphides of iron and copper in intimate association with graphite.†

Prof. J. F. Kemp notes that graphite, or some closely related carbon mineral, is not uncommon in the ore of the Mary mine, at Ducktown, Tenn. He says, "It must have been introduced as some gaseous or very mobile liquid hydrocarbon, which has penetrated into minute cavities and filled larger cracks, and has been subsequently changed to graphite."‡

Von Cotta, in his "Treatise on Ore-Deposits," cites many instances of the influence of carbon on the localization of ore-deposits. A single quotation is selected: "Near Freiberg the veins . . . are enclosed in mica schist which contains an irregular layer of black graphitic schist. . . . The veins have only been found productive in the black schist. In the common mica schist they are very poor."§

Silver Islet.—In the Silver-Islet mine, Lake Superior, graphite was found associated with native silver, silver-glance, tetrahedrite, argentiferous galena and a number of rare silver minerals, in a gangue of quartz, calcite and rhodochrosite. The geological formation is gray slate, nearly horizontal in bedding, traversed by steeply dipping, parallel dikes of diorite and other igneous rocks. The vein cuts vertically across the dikes and

* "Ore-Deposits of the Black Hills of Dakota," by Franklin R. Carpenter, *Trans.*, xvii., 582.

† *Genesis of Ore-Deposits*, pp. 207–209; *Trans.*, xxiii., 605, 606. See, also, on this subject, "The Origin of the Gold-Bearing Quartz of the Bendigo Reefs, Australia," by T. A. Rickard, *Trans.*, xxii., 314, 315.

‡ "The Deposits of Copper-Ores at Ducktown, Tenn," by J. F. Kemp, *Trans.*, xxxi., 261.

§ *Treatise on Ore-Deposits*, Prime's Translation, pp. 46, 47.

the belts of slate included between them, but was ore-bearing only where it faulted the main dike of diorite. This dike, about 200 ft. in width, was in certain places strongly impregnated with graphite.* Intersecting fissures appear also to have had an influence on the localization of the ore. Two bonanzas were discovered: (1) The main ore-shoot (that produced over $2,000,000) extending from the surface to a depth of 330 ft., nearly to the 7th level, and formed at the intersection of a cross-vein with the main lode; (2) the rich body of native silver on the 3d and 4th levels, south (that yielded 800,000 oz. of silver), occurring near the junction of the two branches of the vein. Graphite was not found in the slates, or in any dike of the igneous belt intersected by the vein-fissure, with the exception of this particular dike, which in its limited outcrop above the surface of the lake, at the point where the lode cut through it, formed Silver Islet. The vein in no place carried workable ore-deposits, either in the slates or in the normal diorite. Before the mine was closed down, a small body of ore (that produced about $30,000) was struck on the 13th level, south. Like the larger ore-bodies in the upper-levels, the ore was found to occur in association with graphite. McDermott, writing of this mine, says: "The fact most striking, to one who examines the parts of the vein from which the most valuable ore has been extracted, is the evident connection of the deposit of the silver with the region of graphite impregnation of the wall-rock."†

Graphitic Anthracite.

An extensive deposit of graphitic anthracite, associated with antimonial silver-lead ores, was found in the Parker mine, in

* "The trap-dike has usually been called diorite, but is determined to be norite by Wadsworth, *Bull.* No. 2, *Minn. Geol. Sur.*, p. 92, and gabbro by Irving, Monograph V., *U. S. Geol. Sur.*, pp. 378, 379." *Ore-Deposits of the U. S. and Canada*, by J. F. Kemp, p. 283.

† "The Silver-Islet Vein, Lake Superior," by Walter McDermott, *Eng. and Min. Jour.*, vol. xxiii., pp. 54, 55 and 70, 71.

"The Silver-Islet Mine and Its Present Development," by Francis A. Lowe, *Eng. and Min. Jour.*, vol. xxxiv., pp. 320–323.

"Silver Islet," by Thomas Macfarlane, *Trans.*, viii., 226–253.

"The North Shore of Lake Superior as a Mineral-Bearing District," by W. M. Courtis, *Trans.*, v., 473–487.

"Silver-Islet Mine, Lake Superior" (author unknown, with longitudinal section of the mine, Supplement No. 1, by W. M. Courtis), *Eng. and Min. Jour.*, vol. xxvi., p. 438.

Idaho. The vein occurred in a belt of graphitic lime-shales, about 600 ft. in width, included between two intrusive sheets of andesite; the whole formation—the vein and the igneous sheets bounding the shales above and below—dipping into the mountain at an angle of 40 degrees. The ores were galena and polybasite, averaging (in car-lots) from 75 per cent. of lead and 125 ounces of silver to 45 per cent. of lead and 680 ounces of silver per ton. The gangue was an intimate mixture of white crystalline calcite and quartz. An intersecting vein, coming in from the foot-wall, carried crystallized pyrite and blende, with only traces of silver. The mine produced $365,000. At a vertical depth of 300 ft. from the surface a flat fissure was encountered, filled with graphitic anthracite with a little white quartz intermixed. It formed a flat sheet, 2 to 6 ft. in thickness, and was explored over an area 200 ft. square. The coal was heavily slickensided, crushed and compacted into a hard, granular mass. It was mined with difficulty with a pick, and often required blasting, owing to the stringers of quartz distributed through it. Analysis gave, excluding ash, 90 per cent. of fixed carbon and 10 per cent. of volatile matter, mostly water from the clay contained in the ash. Owing to admixture of quartz and earthy material from the walls, the ash varied from 10 per cent. to 50 per cent. This coal had evidently been formed by the destructive distillation of asphalt or petroleum, filling the fissure. The intrusion of the sheets of volcanic rock enclosed the shale stratum as if in a retort. There is evidence, in the large amount of graphite in these shales, that they were originally highly charged with bituminous matter. The hydrocarbons, first distilled by the heat accompanying the intrusion, were condensed and accumulated in the fissure as heavy petroleum or asphalt, and, by further action of heat, carbon was deposited, hydrocarbon oils being driven off in the same way as in the distillation of petroleum-tar in the manufacture of lubricating oils. Subsequently the deposit was crushed by faulting movements of the beds, and at a still later date the ore-deposits were formed in the intersecting vein-fissure. In places the ore lies against and extends into the coal. Natural gas was not encountered, though conditions were favorable for its formation, probably because the workings were near the surface. Heavy flows of carbonic acid gas were, however, fre-

quently encountered in the mine; and during occasional periods of low atmospheric pressure the outflow of gas from the seams and fissures in the country-rock was so much increased that the miners were often driven from parts of the mine that were not well ventilated.*

J. B. Farish notes that the seams in the limestones at Newman Hill, near Rico, Col., were filled with carbonic acid gas.†

Charcoal.

Native charcoal, or mineral-charcoal, as it is termed, is probably never pure carbon, yet the amount of hydrogen contained is so small that in the discussion of its reducing power it may be classed with graphite. Observation shows that charcoal, from its soft, porous structure, and from the great surface it exposes to chemical action, is one of the most energetic deoxidizing agents in the formation of ore-deposits.

Small pockets filled with charcoal were found at a depth of 800 ft. in the ore-chimney of the Bassick mine, near Silver Cliff, Colorado. This remarkable occurrence of charcoal in an eruptive formation is set forth in detail in the paper by L. R. Grabill.‡

In the discussion of this paper, the occurrence of charcoal in anthracite was described by C. A. Ashburner; and of charcoal in Oregon, formed by the carbonization of the leaves and twigs of plants in the layers of mud between successive overflows of lava, by Dr. R. W. Raymond.§

President Rothwell remarked: "Charcoal has also been found in the silver-bearing sandstones of Southern Utah. These sandstones are a simple sedimentary formation, and contain trunks of trees, some finely silicified. . . . I have also found there pieces of lignite, with the structure of the wood still quite evident. . . . Other portions of the carbonaceous matter have almost the character of charcoal; the carbon has not become hard, nor taken on the form of lignite. The woody

* "Graphitic Anthracite in the Parker Mine, Wood River, Idaho," by W. P. Jenney, *School of Mines Quarterly* (1888–89), vol. x., pp. 313–315.

† "On the Ore-Deposits of Newman Hill, near Rico, Colorado," *Proceedings of the Colorado Scientific Society*, vol. iv., p. 153.

‡ "On the Peculiar Features of the Bassick Mine," by L. R. Grabill, *Trans.*, xi., 110–120.

§ *Ibid.*, p. 119.

fiber of ordinary charcoal can be traced in it very clearly. . . . In the silver-bearing portions of the beds, the charcoal, the lignite, or the silicified wood, as the case may be, is impregnated with chlorides or sulphides of silver, and is in many cases quite rich."*

The deposits of silver-ore in sandstone at Silver Reef, Utah, are mainly due to the reducing action of wood and plant remains, more or less perfectly altered to lignite, and are treated in more detail under that head.†

VII. The Occurrence of Carbon Combined with Hydrogen.

Bituminous Coal.

Blende and galena have been deposited in coal in the outlying basins of the Coal Measures, scattered along the broad, northern marginal belt of the Ozark Uplift.

Near the reservoir at Sedalia, Mo., a basin in the Second Magnesian Limestone carries a little coal of fair quality, in which dark brown crystalline blende occurs in small irregular bunches and in sheets filling both the vertical and horizontal seams and joints. The greater part of the blende is in sheets, $\frac{1}{2}$ to $1\frac{1}{2}$ in. thick, made up of agglomerated imperfect crystals, compressed or flattened between the layers of the coal. Some specimens show blende in thin parallel seams, not thicker than a sheet of paper and $\frac{1}{32}$ to $\frac{1}{16}$ in. apart, distributed regularly through the coal. About 2 tons of blende were mined at this locality.

In Morgan and Moniteau counties, Mo., in a number of places, blende and galena are found in similar deposits of coal. At Martin's coal-bank, near Versailles, Mo., the coal has evidently been disturbed since its deposition, and vertical seams in the coal, $\frac{1}{4}$ in. to 1 in. in width, are filled with sheets of crystalline blende and galena in a gangue of calcite and white tallow-clay. The strike of the lines of disturbance of the coal, prolonged 500 to 1000 feet southerly, crosses an extensive tract of old surface-workings in the Second Magnesian Limestone. The ground is thickly covered by shallow pits, dug in search of lead-ore. These deposits of lead were apparently formed

* *Ibid.*, pp. 117, 118.

† See pp. 322-327.

through the agency of the same system of fissures that introduced the ore in the coal.

Blende and galena were formerly mined at Simpson's coal-bank, in Moniteau county. The coal is a hard cannel, filling a basin in the Second Magnesian Limestone; the ores occur in seams, seldom more than an inch in thickness, in the joints of the coal. The ore incidentally obtained in mining the coal afforded an occasional shipment to the smelters.

Vanadium is found in a lignite coal in the province of Mendoza, Argentine Republic. The ashes of this coal carry vanadic acid, V_2O_5. It also occurs in anthracite mined near Yauli, Peru.*

Gold has been repeatedly reported in the ash of the Cretaceous coals of the West. H. M. Chance records that the coal of the Cambria Coal Co. near Newcastle, Wyoming, is said, by the chemist of the company, to carry gold.† Mr. H. Rives Ellis, of Salt Lake City, informs the writer that he obtained an average of 60 to 80 cents gold per ton of ash from the Pleasant Valley, Utah, and Kemmerer, Wyoming, coals. In this connection, the paper by G. A. Koenig and M. Stockder‡ is of interest, although the coal described appears to be more nearly an infusible hydrocarbon, such as might result from the partial oxygenation of albertite.

Mr. Henry Sewell describes the occurrence of antimonial silver-ores, in association with strata carrying beds of bituminous coal, in the mineral caves of Huallanca, Peru, located at an elevation of 14,700 ft. above the sea. These silver-mines are situated in a coal-formation, upturned on edge by an outburst of porphyry, the upheaval forming immense backbones, with the stratification standing almost perpendicular. A bed of coal is mined for blacksmithing purposes within a distance of 150 yards of the ore-bearing beds. The ore is tetrahedrite, with about 800 ounces of silver per ton, and occurs lining cav-

* 21*st Annual Report of U. S. Geol. Sur.*, 1899–1900, Part VI.; *Mineral Resources of the U. S.*, p. 315.

† "The Discovery of New Gold Districts," by H. M. Chance, *Trans.*, xxix., 227.

‡ "On the Occurrence of Lustrous Coal with Native Silver in a Vein in Porphyry, in Ouray County, Colo.," *Trans.*, ix., 650. See, also, "Modes of Occurrence of Pyrite in Bituminous Coal," by Amos T. Brown, *Trans.*, xvi., 539–546.

erns, in beds of sandstone. Some of these caverns are 25 to 30 ft. long and of nearly equal height, their inner surfaces covered with a coating 2 to 3 in. thick of crystallized silver-ores, mostly tetrahedrite. Silver-ores also occur in the shale beds adjacent to the sandstone.*

Lignite.

At Silver Reef, Utah, silver has been deposited in lignitic-sandstones, determined by Newberry to be of Triassic age.† The mines since 1885 have only been worked by leasers in a small way. During the height of production in 1877–79, the total output was 2,122,471 ounces of silver.‡ The ore-bearing beds were 30 to 40 ft. in thickness, of which usually only 16 ft. was pay-ore. The ore occurred in flat shoots that were, in some places, 300 ft. wide, and extended 400 to 500 ft. deep on the dip of the formation. The ore was richest near the outcrop, and, as it was followed in depth, gradually got poor. Near the surface the silver was in the form of chloride, associated in places with the blue and green carbonates of copper in very small quantity. As the ore was followed in depth, the chloride gave place to silver-sulphide, and scales of native silver came in, especially in the branches of trees and distributed in the plant-shales. No other ores were found, and the gangue-minerals usually occurring in ore-deposits, as quartz, calcite, barite, etc., were absent. When, following the inclination of the strata, the workings attained a vertical depth of 400 to 500 ft., the ore changed, becoming low-grade and difficult to amalgamate in pans; the ore-shoots at the same time contracted, becoming narrow, and only 2 or 3 ft. in height. Exploration was continued for several years, but finally all search in depth for pay-ore was abandoned.§

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* "The Silver Caves of Peru," by Henry Sewell, *Eng. and Min. Jour.*, vol. xxiv., p. 292. Abstract taken from the *London Mining Journal.*

† "Report on the Properties of the Stormont Silver-Mining Company at Silver Reef, Utah," by J. S. Newberry, *Eng. and Min. Jour.*, vol. xxx., p. 269. See, also, "The Silver Reef Sandstones," by J. S. Newberry, *Eng. and Min. Jour.*, vol. xxxi., p. 4.

‡ *Eng. and Min. Jour.*, vol. xxix., p. 26.

§ "Silver Reef District, Southern Utah" (author unknown), *Eng. and Min. Jour.*, vol. xxix., pp. 25–26, 45–46, 59–60, 79–80, and 96.

"The Silver Sandstone District of Utah," by C. M. Rolker, *Trans.*, ix., 21.

"The Peculiar Features of the Bassick Mine;" Discussion by R. P. Rothwell, *Trans.*, xi., 117–119. *Genesis of Ore-Deposits*, pp. 130, 131.

Many writers report that traces of silver and copper occur in the extension of these same sandstone reefs, which can be traced by their outcrop for a distance of 10 to 20 miles to the southwest. An unknown author, in the early development of the district (May, 1877), thus describes the peculiar occurrence of the ore: "The formation is a beautifully stratified red and white sandstone, but greatly broken up and eroded. Where the strata have been undisturbed they rise to a height of perhaps a thousand feet above the adjacent valley, in table-mountains, alternately banded in red and white, and plainly showing the former height of the whole country. The numerous extinct volcanoes and the vast quantities of volcanic rock found throughout southern Utah, and particularly this section, point to at least one agent, and, no doubt, a powerful one, which served to produce the numerous foldings and contortions of the strata, while the great sandy deserts, covered with sage and cactus, bear abundant evidence to the erosion. On the northern side of what was once a vast basin, lying between several ranges of high mountains of old rock, where the erosion of an anticlinal has left ridges of reefs cropping out at various angles, are situated the mines. . . . The sandstone consists of red and white deposits, carrying some lime as a cementing material, with occasional layers of clayey or shaly rock, and considerable carbon scattered throughout. This carbon, which is evidently from the decomposition of drift material, of which the impression in the rock and even the *plant itself* is yet distinct, occurs in important layers in places. . . . Petrifactions, even of the size of large trees, are not uncommon, some of which form a valuable ore. The white sandstone, which appears to be of a somewhat finer texture than the red, seems, so far, to have carried the ore. . . . These veins, as they are there called, are entirely conformable with the strata, and in no case do they cut across the adjacent layers of rock. They appear to be richest where there is the most carbon, which evidently has acted as a reagent to precipitate the silver from solution and to deposit it, sometimes as flakes of metallic silver, in its midst. In some cases the form of the plant, of apparently a reedy nature, is yet distinct, in which the cells are yet visible, but to a great extent filled with valuable ore. Other beds carry considerable copper in the form of blue or green

carbonate, and also iron in nodules which run very high in silver. . . . A light sandstone, containing streaks or fine layers of a dark material, which elsewhere would not attract attention, is there found, sometimes, to run from $50 to $100 a ton; while the darker rock, containing considerable carbon, copper, or iron-nodules, will at times run into the hundreds, or even thousands."*

Mr. Watson M. Nesbit, who was connected with mining operations at Silver Reef from 1878 to 1888, gives the author the following statement of the manner of occurrence of the ore: In the Barbee and Walker mine, water was struck at a depth of about 500 ft. vertically. Near that point the ore changed in appearance and character, and gave great trouble in amalgamation, the extraction being very low. The ore was treated hot, in pans; a thick scum rose on the pans, like heavy petroleum oil, and had to be removed from time to time during the amalgamation. From a charge of 1½ tons of ore, as much as a gallon of this oily material would be obtained. The ore at water-level, if carefully stoped, averaged 12 to 16 oz. of silver per ton; but only a part of the silver could be saved in pans. A very little pyrite appeared at water-level—the first seen in the mines. About 100 to 200 ft. above water-level, on the slope of the beds, the ore was in places very rich; and small bunches of lignite coal, 4 to 10 in. across, were found imbedded in the soft sandstone, with native silver deposited in thin scales on the joints of the coal. Most of the ore at this depth was silver-sulphide. At one place a tree-trunk, 18 in. in diameter, was found; the heart-wood was silicified and very hard, and carried 8 to 10 oz. of silver per ton. The sap-wood and bark, 3 to 6 in. in thickness, were altered to soft, crumbling lignite, full of silver-sulphide; it assayed 5000 oz. of silver per ton. The ores from the Silver Reef mines never showed any gold by assay; but in leaching the ore by the Russell process, the silver-sulphides produced contained a trace of gold.

Review of the Phenomena at Silver Reef.—Light is thrown on the change in the mineral character of the ore at water-level, and on the difficulty experienced in amalgamation, by the dis-

* "The Silver Sandstones of Utah," by C. F. A., Salt Lake City, *Eng. and Min. Jour.*, vol. xxiii., p. 317.

covery announced by Newberry* that the ores carried selenium, —the average of four analyses giving selenium, 0.23 per cent., and silver, 0.26 per cent. The selenium in one specimen amounted to 90 ounces per ton.

Whether the silver was deposited at the same time the sediments were laid down, or was introduced by solutions upflowing through faulting-fissures in a later geological age, has been a much debated question. Without dwelling upon this point, —for, in either event, the primary deposition of the ore was due to the hydrogen and carbon of the plant-remains enclosed in the sandstones,—certain peculiar features of the occurrence deserve notice. The structure at Silver Reef may be stated as a broad anticlinal arch, broken up by faults coursing northerly and southerly, rudely parallel to the axis of the fold. A basin, nearly 3 miles across, occupied by the valley of the Virgin river, was eroded through the crest of the arch, leaving the two cliffs facing one another, the strata dipping away from the basin on the two sides. The total area of the several ore-producing belts of sandstone-outcrop, left by erosion, covered less than 500 acres.

Silver Reef conforms to the general law of areal distribution of mining-districts, namely, that "*Ore-deposits have been formed only in local areas of disturbance. Between and surrounding such areas of mineralization extend broad, barren tracts of undisturbed strata,*"† and also conforms to the law of mineral occurrence, namely, that "*All workable deposits of ore occur in direct association with faulting-fissures traversing the strata, and with zones or beds of crushed and brecciated rock, produced by movements of disturbance. The undisturbed rocks are everywhere barren of ore.*"‡ The descriptions apply to a mineral area which, prior to the recent erosion of the basin, may have possibly covered four or five square miles, with pay-ore found in no place outside this special area.

A writer notes that only the fractured, jointed and permeable portions of the bed are rich; where undisturbed and massive, the sandstone is barren. Also that vertical fault-

* "The Silver Reef Sandstones," by J. S. Newberry, *Eng. and Min. Jour.*, vol. xxxi., p. 5.

† "Lead- and Zinc-Deposits of the Mississippi Valley," by W. P. Jenney, *Trans.*, xxii., 192. ‡ *Ibid.*, p. 184.

planes frequently bound the ore.* These are conditions that are found in impregnated beds of zinc- and lead-ores in Southwest Missouri and Northern Arkansas, and also in the flat deposits of gold, associated with tellurium, in the Cambrian sandstone near Deadwood, South Dakota.

Selenium usually occurs with minerals believed to have been formed by highly-heated vapors and solutions and in direct association with igneous disturbances. Its presence at Silver Reef seems to favor the theory of the deposition of the silver through the fissures. It appears that secondary enrichment has taken place on an extensive scale, and that the silver was deposited originally in the sandstone in combination with selenium and probably with sulphur by the reducing action of the lignitic matter. Afterwards, these primary ore-bodies were enriched by the secondary precipitation of silver-sulphides, by the agency of descending surface-waters, aided greatly by the progressive erosion of the basin. In this migration of the ore—the outcrop of the sandstone gradually disintegrating and wearing away from exposure to weather—to the deposits of silver-sulphides, re-formed at deeper levels on the dip of the same beds, the reducing agent has been the organic material distributed through the ore-horizon. Later, these reinforced ores were, near the outcrop, altered to silver-chloride, cerargyrite, the trace of copper occurring with the silver forming the carbonates, azurite and malachite. When the mine-workings passed below this zone of enrichment there were found only small bodies of ore, that had remained unaltered since the first deposition of silver in the beds.

Similar occurrences have been described of copper-ores replacing the wood of trunks and branches of trees, and encrusting the leaves and stems of fossil-plants, in the Triassic sandstones of New Mexico,† and in the Permian sandstones of Russia.‡

E. J. Schmitz writes of the occurrence of copper-ores as

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* "Silver Reef District, Southern Utah," by R. P. Rothwell or Thomas Couch (?), *Eng. and Min. Jour.*, vol. xxix., pp. 25–26.

† "The Origin of Copper- and Silver-Ores in Triassic Sand-Rock," by F. M. F. Cazin, *Eng. and Min. Jour.*, vol. xxx., p. 381. "The Silver Reef Sandstones," by J. S. Newberry, *Eng. and Min. Jour.*, vol. xxxi., pp. 4–5.

‡ *Trans.*, ix., p. 33.

pseudomorphic replacement of wood and branches of trees in bituminous clay-slate in the Permian of Texas.* In the discussion of this paper, Mr. Henry Louis describes deposits somewhat analogous in the Permian of Nova Scotia, at New Annan, where the ore occurs in nodules of chalcopyrite, chalcocite, and iron-pyrites,† associated with plant-remains converted into anthracite.

Posepny also describes remarkable specimens of tree-trunks altered to galena from the Vesuvius mine, Freihung, Bavaria.‡

Bituminous Shales.

Rich deposits of blende, formed in great part by the secondary enrichment of smaller, or less mineralized, primary ore-bodies, are found near the surface in the Joplin, Mo., district, in the vicinity of Carthage, Lehigh, Central City and Reding's Mill. At these localities the ore occurs in two ways: in the beds of soft, decomposed carbonaceous shales in the Coal Measures, occupying shallow basins in the Subcarboniferous limestone of the region; or, more commonly, in horizontal channels eroded in the underlying limestone and filled with soft, dark mud, intermixed with bituminous matter, derived from these same shales, crushed by faulting movements and washed into the openings by surface-waters. Without regard to the character of the enclosing formation, these forms of ore-deposit are known to the miners as "mud-runs." These occurrences are seldom far from the surface; the deepest "run" of this character observed, near Reding's Mill, was at a depth of 90 ft. At Lehigh, similar deposits were found in the bottom-lands along the stream, within a few feet of the surface, where the permanent water-level came near to the top of the ground.

The ore occurs in minute crystals, thickly disseminated through the soft, shaly gangue, or enveloped in semi-fluid black mud. In some of the deposits the crystals of blende are agglomerated, forming irregular masses and sheets of pure ore. The crystals are of uniform size, usually from $\frac{1}{16}$ to $\frac{1}{8}$ of an in.

* "Copper-Ores in the Permian of Texas," by E. J. Schmitz, *Trans.*, xxvi., 101.

† "Copper-Ores in the Permian of Texas;" Discussion by Henry Louis, *Trans.*, xxvi., 1051, 1052.

‡ *Genesis of Ore-Deposits*, pp. 129, 130.

in diameter, transparent, resin-yellow in color, with a shade of red, resembling in appearance the small garnets found in some placer gold-bearing gravels. The small size of the crystals is probably due to the concentration of the solutions from which they were deposited, and to their rapid formation. In some instances blende forms crystals in these shaly beds from ½ in. to more than an inch in diameter, presumably from a slower and more prolonged growth. In all the deposits of this type, the reducing agent has been bituminous matter acting upon surface-waters, which carried in solution the sulphates of the metals leached from ore-bodies at higher levels, that were undergoing oxidation. The following equation shows the character of the change:

$$ZnSO_4 + 2CH + H_2O + O = ZnS + 2H_2CO_3.$$

It has been observed that these shallow mud-runs usually occupy synclinal basins or troughs, and that surface-erosion has often removed a considerable depth of the ore-bearing formations from the immediate vicinity; the deposits being located where they have received the drainage from surrounding mineral-areas.

At the Britton mine, Central City, the ore occurs at a depth 40 to 50 ft. from the surface, in a broad, flat, compound-run, 75 to 150 ft. wide and 6 to 12 ft. high, developed on its course for a length of 550 ft., northerly and southerly.* The ore is granular, crystallized blende in a stratum of soft, black mud and broken chert. The particles of blende are less than $\frac{1}{16}$ in. in diameter, deep garnet-red in color, and, although thickly distributed in the mud, are not agglomerated. A number of similar deposits are developed in the vicinity.

Ore-deposits of this character are easily mined with pick and shovel; powder is only used to break up an occasional boulder in the ore-body. The ore requires very little crushing and readily concentrates, yielding from 12 to 20 per cent. of clean blende. The product is very pure, assaying from 62 to 64 per cent. of metallic zinc.

Reding's mine, about 4 miles southeast of Joplin, is situated

* For a definition of these forms of ore-deposits, see "The Lead- and Zinc-Deposits of the Mississippi Valley," by W. P. Jenney, *Trans.*, xxii., 189, 190.

in a shallow basin in a low range of hills, bordering the north side of the valley of Shoal creek. At the time of the examination, this mud-run was opened 75 ft. in length, north and south, with a width of 36 ft., and a height of 12 to 18 ft. The ore occurs in dark-brown mud, in finely disseminated crystals, and in crystallized masses and sheets of galena and blende. Beautiful specimens of galena are found in very perfect cubical crystals, 1 to 2 in. on a side. The upper part of the run is mostly crystallized galena, while the lower part is blende, with a smaller proportion of galena. Boulders of flint and black clay-shales are found in the ore, together with much coarsely crystalline rotten dolomite.

This ore-deposit is remarkable for its extreme richness. To the date of my examination, the yield of the mine, estimated upon all material extracted, had been 15 to 20 per cent. of clean ore. When first formed, it was evidently a small run of blende and galena in dolomite; subsequently, surface-waters eroded a cavern-like channel following the course of the run. Material washed from the surface formations of broken and crushed bituminous shale filled this channel and enveloped the ore-body. Finally, the ore primarily deposited was greatly reinforced by secondary deposition, both galena and blende being crystallized in the fluid mud by the reducing action of the hydrocarbon.

A small basin of coal-shales, near Belleville, Jasper county, Mo., carried beautifully preserved fossil-plants. The outer surface of the mass of shales, for a depth of about a foot, contained scattered crystals of blende, from $\frac{1}{4}$ to $\frac{3}{4}$ in. in diameter, mingled with a few crystals of galena and pyrite. The central portion did not carry any mineral, the mass having been mineralized from the outside, toward the interior, as far only as the mineral-bearing waters could penetrate the dense plastic clay. The crystals, in their growth, have distorted otherwise perfect fossil-plants, crowding parts of the fern-fronds to one side; giving evidence that the deposition of the minerals was of later date than the preservation of the plant-remains. These plants were determined by David White to belong to a horizon near the middle, or the upper part, of the Lower Coal-Measures.*

* "Flora of the Outlying Carboniferous Basins of Southwestern Missouri," *Bulletin of U. S. Geol. Sur.*, No. 98.

On the Mine La Motte grant, in Southeast Missouri, deposits of disseminated galena in black shale of Cambrian age outcrop at the surface, and were worked for lead during the early period of mining in that region. The galena occurs in crystalline nodules, from $\frac{1}{4}$ to $\frac{3}{4}$ in. in diameter, thickly distributed in bands through the shale. This shale-bed appears to be a local formation. The ore-deposits closely resemble in mode of occurrence those of disseminated lead in the Cambrian limestone in the belt extending from Mine La Motte, through the Flat River district, to Bonne Terre.

The secondary formation of metallic sulphides is now taking place in the Missouri mines; blende and galena, oxidizing to sulphates in the ore-deposits near the surface, are carried in solution by the subaërial waters to the deeper horizons, and there regenerated by the deoxidizing action of bituminous matter. The subject is too extensive to admit of discussion here, and must be left for a future paper.

A single instance, however, may be cited of the reproduction of blende from mine-waters. An old tunnel, driven through bituminous shale on the Banker's Tract, near Joplin, became filled with water draining from adjoining mines on which work had been suspended. The tunnel remained closed and submerged for ten or twelve years, until the mines were unwatered in 1898. When reopened, the surface of the shales, on the roof and sides of the tunnel, was found to be thickly encrusted with minute crystals of blende, one- or two-hundredths of an inch in diameter. In places, the blende was deposited on the pick-marks made when the tunnel was run.

The paper of T. A. Rickard, on "The Enterprise Mine, Rico, Colorado,"* shows the existence of a strongly-marked resemblance between the occurrence of the flat ore-deposits at Rico, carrying silver and gold, and the ore-formation of Southwest Missouri, where galena and blende occur in simple runs, and also in compound runs, formed in like manner, in the favorable beds, by mineral-depositing solutions introduced through vertical fissures from an unknown source in depth, and where bituminous matter, contained in the ore-bearing strata, has likewise been the precipitating agent in the deposition of the ore.

* *Trans.*, xxvi., 906–980.

Experiments made in the laboratory, to determine the reducing action of the black shale associated with the ore-bodies, are described by Rickard, as follows:

"A piece of the Rico shale was put into a weak solution of sulphate of silver (Ag_2SO_4) containing some free acid intended to neutralize the lime ($CaCO_3$) in the shale. The precipitation of metallic silver became visible in three days. The parallel experiment with gold was more interesting. A piece of ore (assaying 1147 oz. of gold per ton) obtained from . . . . Cripple Creek, was taken, and its gold was extracted by a solution containing ferric sulphate ($Fe_2O_3,3SO_3$), common salt (NaCl) and a little free acid (H_2SO_4). This Cripple Creek ore carried the black oxide of manganese (MnO_2) in visible quantity, and thus the chlorine used to form the gold-solution was liberated in a manner simulating natural conditions. Of the gold, ... 99.91 per cent. was extracted and subsequently precipitated on the Rico shale by inserting the latter in the solution thus formed. The gilding of the black shale by the deposit of gold became visible within four hours."*

W. Nicholas has made a series of similar experiments in the precipitation of gold by black carbonaceous shales from the Victorian quartz-reefs.†

The peculiar vein-formation known as the "Indicator" is an example of the localization of rich deposits of free gold, due to the reducing action of carbonaceous shales. Rickard defines the Indicator as "a very thin thread of black slate, which is remarkable on account of its extraordinary persistence, and also because the quartz seams which cross it are notably enriched at the point of intersection."‡ It is also referred to by Dr. Don.§ The Indicator is the most important member of a series of thin seams of black shale, more or less impregnated with pyrite and arsenopyrite, traversing the slate and sandstone formation of the district.

Different views have been expressed as to whether the car-

* *Ibid.*, pp. 978, 979.

† "The Origin of the Gold-Bearing Quartz of the Bendigo Reefs," by T. A. Rickard; Discussion, *Trans.*, xxii., 762–763.

"The Origin of Gold in Certain Victorian Quartz-Reefs," by William Nicholas, *Eng. and Min. Jour.*, vol. xxxvi., pp. 367, 368.

‡ "The Indicator Vein, Ballarat, Australia," *Trans.*, xxx., 1010.

§ "The Genesis of Certain Auriferous Lodes," This volume, p. 162.

bon or the pyrite in the Indicator seam was the reducing agent in the formation of the rich bunches of gold-ore. But pyrite was deposited in the black shale by the reducing action of the organic matter; so that, in any event, it was the presence of carbon compounds which, directly or indirectly, caused the local accumulation of the gold.

Owing to the far more powerful action of the hydrocarbons, reduction by pyrite contained in carbonaceous shales must always be subordinate, even where local conditions, such as the presence of free oxygen and oxidized metallic salts, admit of the pyrite being decomposed. Any ferrous sulphate produced, at once re-forms pyrite, giving up its oxygen to the carbon. In the depths of the strata, below water-level, wherever any form of carbon is in excess, it absolutely protects the pyrite by consuming all the free oxygen.*

Many instances might be cited to illustrate the influence of the organic matter contained in bituminous shales upon the formation of ore-deposits.

A stratum of black shale in the Mono silver-mine, Dry Cañon, Utah, formed the hanging-wall of the rich ore-shoot, from which large masses of horn-silver and high-grade sulphide-ores were mined, carrying from 500 to 3000 oz. of silver per ton. It is reported that a carload of ore from this mine yielded over $55,000.

Emmons says: "Most famous, in view of the enormous values taken from them, are the rich silver-bodies of the Mollie Gibson and Smuggler mines of Aspen, Colo.; but, in their case, there is sufficient organic matter present to explain the reduction of the oxidized solutions to sulphides. They occur along a vertical fault, formed since the original mineralization of the district, and consist of great masses of polybasite and pink barite, which, in places, have been further reduced to native-silver. On one wall of the ore-body is the limestone, of which it is a replacement, and on the other a black bituminous shale."†

Rickard, discussing this subject, writes: "The idea of the

* This subject is discussed in more detail, under the sub-head, Protective Action of Carbon and of Hydrocarbons, *Ante*, p. 311.

† "The Secondary Enrichment of Ore-Deposits," *Trans.*, xxx., 195. See, also, *Genesis of Ore-Deposits*, pp. 450, 451.

precipitation of the ore through the agency of carbonaceous matter has been advanced in connection with ore-deposits in other regions. I may quote, as instances, the black Silurian slates of Bendigo, Victoria; the Devonian slates of Gympie, Queensland; the Jurassic slates of the 'Mother Lode' region in Calaveras and Amador counties, California; the black shale enclosing the gold-specimen ores of Farncomb Hill, Breckenridge, Summit county, Colorado; . . . and the celebrated Indicator series of Ballarat, Victoria."*

In this connection, reference is made to the well-known occurrence of copper-ores at Mansfeld, Prussia, in beds of bituminous slate and bituminous limestone. Certain of the lower limestone beds are fetid. These copper-bearing formations extend over a large district.† The ore contains so much bituminous matter that only a little brushwood is required in roasting the ores in piles.

Limestones Containing Organic Matter.

In mining-regions where the ores occur in limestone, it is observed that in most instances the largest and most productive mines are in belts or zones of crystalline limestones which are either exceptionally pure lime-carbonates or, more frequently, dolomites with only a small amount of insoluble matter. Such formations, peculiarly favorable for ore, are rocks easily crushed by movements of disturbance, readily permeated by circulating-waters, and, from their chemical composition, rapidly attacked by solutions carrying carbonic acid. Where situated at the surface, they are cavern-forming limestones. Further, it is noted that both the magnesian limestones and the pure lime-carbonates usually contain some form of organic matter which, though small in amount, appears to have strongly influenced the deposition of the minerals in the strata.

Otherwise stated, ore-deposits in limestone, irrespective of the nature of the minerals constituting the ores, conform to the general law of selective deposition, namely, that "*Some geological formations appear to be everywhere barren of ore; others occasionally carry small deposits, workable where the conditions are*

* "The Enterprise Mine, Rico, Colorado," *Trans.*, xxvi., 978.

† Von Cotta, *Treatise on Ore-Deposits*, Prime's Translation, p. 164.

*exceptionally favorable; but in each mining region certain strata are ore-bearing in a degree exceeding all other formations combined."**

Among the causes that have induced the concentration and deposition of the ores in special formations, prominence may rightly be given to the deoxidizing action of the bitumen, bituminous coal, lignite, or other form of carbonaceous matter disseminated in the rock.

In Southeastern Missouri, the lead-ore now mined is mostly from deposits of disseminated galena in the dark-colored magnesian limestone, rich in bituminous matter, of the Cambrian formation at Bonne Terre and the Flat River mines. Practically all the zinc-ore, and the greater proportion of the lead, produced in the Joplin region, in the southwest part of the State, is yielded by the Cherokee limestone, the upper division of the Subcarboniferous.† The Cherokee is a soft, crystalline, pure lime-carbonate, carrying bitumen. Its average composition, from a number of analyses, is as follows:

Lime,	55.00
Magnesia,	0.23
Alumina,	0.10
Protoxide of Iron,	0.05
Protoxide of Manganese,	0.02
Bitumen and insoluble,	1.00
Carbonic acid,	43.60
	100.00

In the Upper Mississippi lead-region the productive formation has been the Galena limestone, the upper member of the Trenton. It is a soft, crystalline dolomite; bituminous matter is present in relatively small amount, yet apparently more than sufficient to effect the precipitation of the metals and preserve the ores from oxidation below water-level. The deposits of blende in the mines near Mineral Point and Shullsburg, Wisconsin, occur in the underlying "Blue" limestone of the Trenton, and the ores are concentrated about the intersection of the mineral-bearing fissures with thin strata of brown shale, saturated with petroleum,—the "Oil-rock" of the miners.‡

* "The Lead- and Zinc-Deposits of the Mississippi Valley," by W. P. Jenney, *Trans.*, xxii., 187–188.

† "The Lead- and Zinc-Deposits of the Mississippi Valley," by W. P. Jenney, *Trans.*, xxii., 188.

‡ William P. Blake, Discussion of "The Lead- and Zinc-Deposits of the Mississippi Valley," *Trans.*, xxii., 631.

A summary review of the occurrence of zinc- and lead-ores in the Mississippi valley shows that the formation of the deposits has been due to solutions of normal temperature; and that the chief agent in the primary deposition, and in the secondary enrichment of the ores, has been the bituminous substances contained in the strata in which the deposits are found. The larger part of the minerals constituting the ores has been deposited either by crystallization or by crystalline growth in the lime-rock or dolomite of the walls, or has impregnated the beds of specially favored geological formations.

In the limestone-area at Tintic district, Utah, the productive mines occur in two distinct belts in the Carboniferous formation; one, extending through the central part of the district, of dark-colored, magnesian limestones; the other, traversing Godiva mountain, on the eastern border of the lime-area, formed by beds of gray limestone with only a trace of magnesia.

On the central belt are situated the Gemini, Bullion-Beck, Eureka Hill and Centennial Eureka mines; and farther south, also in magnesian limestones, are located the Grand Central and the Mammoth. A number of these mines have been worked continuously since the early development of the district in 1870–71. All have reached a depth of 1000 to 1750 ft.; the Mammoth is now 2100 ft. deep.

It is not necessary to discuss the occurrence of the ore, beyond its relation to the magnesian limestones in which the deposits are found. Locally, these limestones vary somewhat in character; they are hard, crystalline, bluish-gray to bluish-black dolomites, the color being due to organic matter. In certain places the beds are filled with nodules and thin bands of hard, black chert. The average composition, from 7 analyses, of the limestones in the vicinity of the Bullion-Beck mine is (the organic matter and loss being estimated by difference):

Calcium carbonate,	48.76
Magnesium carbonate,	35.43
Ferrous carbonate,	2.61
Silica,	9.67
Alumina,	3.00
Organic matter and loss,	0.53
	100.00

In a number of analyses the silica varied from 6.75 per cent.

to 13 per cent., and the total insoluble matter from 16 per cent. to 18 per cent.

The amount of silica and insoluble matter is remarkable, for there is every evidence in the mines that these dolomitic limestones are rapidly decomposed and eroded by carbonated waters. The explanation of this marked solubility of the dolomite, notwithstanding the large proportion of impurities, is probably to be sought in the structure of the rock. In the upper levels of the Bullion-Beck and the Eureka Hill mines, where the subterraneous erosion by surface-waters has been greatest, large masses of residual dolomite sand, which have resulted from the disintegration of the fissured and shattered beds, occur, filling cavern-spaces or chambers in the limestone. Beneath the heavy wash of boulders filling the gulch, the limestone beds, for a depth of near 100 ft., without change in the stratification, are decomposed and altered *in situ* into soft, sandy dolomite, stained with iron and manganese oxides. Analyses showed that this decomposed rock had substantially the same composition as the loose deposits of sand; being dolomite, with the residual silica, clay, oxidized iron and manganese contained in the original formation. Surface-waters, carrying carbonic acid, appear first to attack the calcareous cement between the crystalline grains of dolomite, at the same time oxidizing the carbonates of manganese and iron present, and in this way rapidly disintegrate the rock.

Many caverns, mostly of small size and usually more recent in formation than the ore-bodies, occur in the limestone. It is noted that they are generally located along the course of the vertical faulting-fissures, which have been the channels followed by the solutions depositing the ore, the shattering and brecciation of the beds, due to the faulting movement, increasing the action of surface-waters in the erosion of the rock.

In a few instances the ore actually fills pre-existing caverns. The largest of these caverns in the Bullion-Beck mine, formed before the minerals were introduced in the primary deposition, was filled with argentiferous galena, in great part deposited by crystallization. The rock-floor of the cavern was covered by a horizontal stratum of chert nodules, overlain by sand-beds, 10 to 15 ft. in thickness, with disseminated pyrite and galena, the

massive crystalline lead-ore resting on the sedimentary beds. The flat-beds covering the clay floor were unquestionably formed from the residual sand and chert contained in the rock, dissolved away by the circulating-waters in making the cavern. Such occurrences of ore deposited by crystallization are rare in these mines; practically all the quartz, and nearly all the lead- and copper-ores, are formed by replacement.

The limestones are much purer in the Grand Central and Mammoth mines. An average of 6 analyses gave (ferrous carbonate, alumina and organic matter not determined):

Calcium carbonate,	55.38
Magnesium carbonate,	42.84
Silica,	0.65
Undetermined and loss,	1.13
	100.00

This is a bluish-gray, brown, or bluish-black, crystalline dolomite, free from chert. The weathered outcrop of certain beds shows the rock to be made up of the broken and water-worn joints of minute crinoid stems, one- to three-hundredths of an inch in diameter, with fragments of shells and an occasional small coral. The stratification is generally preserved; in some places the rock is cross-sheeted by movements of disturbance, and locally the beds have been brecciated and recemented by their own attrition material into a massive rock, with but traces of bedded structure.

This limestone, even where not mineralized, is easily distinguished by the appearance and fracture of the rock,—being dark-colored and crystalline, with spots and small vugs of calcite and stains of iron and manganese oxides on the joints. It is often sonorous, giving a clear metallic ring when struck with a pick. It crumbles under a blow into small, ragged, rough fragments, having the fracture of loaf sugar.

The beds are thin, brittle, easily shattered and crushed by faulting-movements. On account of the absence of clay in the rock, the breccias and attrition-material produced are permeable to circulating-waters; even small fissures and fractures in the lime keep open. Caves of considerable size are not infrequently encountered in the formation, but appear to have been formed subsequent to the ore. It is noteworthy that deposits of loose

dolomite-sands are seldom formed in this pure dolomite; neither is the rock usually altered in place to iron-stained rotten dolomite. The action of surface-waters is to dissolve the rock completely, and not to disintegrate the rock by attacking the calcareous cement between the grains.

The ore-bodies afford evidence that this limestone, especially where fissured and fractured, is easily replaced by silica and by the other gangue-minerals, ankerite, siderite, barite and calcite. Not only has the limestone been metasomatically replaced by primary sulphide-ores, carrying lead, copper, iron, arsenic, silver and gold, but the complex products of their oxidation and redeposition have, also, more or less perfectly replaced the rock. It is observed that the darker and coarsely crystalline lime-beds are highly favorable for ore,—beds made up of comminuted fossil-remains, crinoid stems, broken corals and shells.

Eliminating the highly impure sediments, which seldom carry workable deposits, the structure of the rock appears to be far more important than the chemical composition in determining whether certain strata are ore-bearing or barren. Analyses of the magnesian limestones over a broad belt show that they vary but little in composition. The beds which have been found to be unfavorable for ore are usually dense, finely crystalline and impermeable; the rock generally breaking under a blow of a hammer with a "dead" sound, and a smooth, splintery fracture, like the fracture of quartzite. Organic matter is not at all prominent in this limestone, although it gives the color to the rock.

The principal ore-bearing formation in Godiva mountain is a stratum, 200 to 400 ft. in thickness, of massive, gray, very coarsely crystalline limestone. It is a pure lime-carbonate, carrying some undetermined form of bituminous material, which gives to the rock, when broken, a sulphurous, fetid odor. On dissolving the limestone in acid, the bitumen separates in clots. An analysis of this limestone gave (the organic matter and loss being estimated by difference):

Calcium carbonate,	98.75
Alumina and iron-oxides,	0.40
Silica,	0.20
Magnesia,	trace.
Organic matter and loss,	0.65
	100.00

The weathered outcrop of the gray limestone is, in many places, bluish-black from the concentration of the bitumen in the surface of the rock. The beds are formed of water-worn grains and broken fragments of small shells. A coral (zaphrentis), 1 to 2½ in. long, is its characteristic fossil. It exceeds in chemical solubility all other ore-bearing limestones in this section of the district. The perfect manner in which great masses of the rock are replaced by the ore is evidence of this.

The gray-limestone formation extends northerly and southerly through the whole length of Godiva mountain, bounded on either side by limestones more or less magnesian in character. Many of these magnesian limestones, interbedded in the series, are highly impure sediments, with 25 to 35 per cent. of silica, 5 to 10 per cent. of iron and alumina, 6 to 12 per cent. of magnesia, and 20 to 30 per cent. of lime. These formations have been found unfavorable for ore.

On this gray-lime belt are located the Uncle Sam, May-Day and Yankee Consolidated mines,—properties developed since 1897. The deepest workings have attained a depth of 800 ft. The Uncle Sam mine has been noted for its large output of high-grade lead-ore, carrying silver, in a gangue mainly composed of lime-carbonate.

Quartz-ores prevail in the other mines of the belt, with lead, silver, and usually a small amount of gold.

The ores have been introduced in the strata through belts of nearly vertical faulting-fissures. Along the course of these fissures the ore-bodies have formed in the limestone. In some places the ore-deposits take on the form of fissure-veins, the ore being confined within the walls of the fissure and deposited in a more or less tabular sheet, pitching like the ore-shoots in quartz-veins in the metamorphic rocks. More commonly the faulting movements forming the fissures have so fractured the beds that the mineral deposits are not limited by the fissure-walls and extend irregularly into the limestone. The largest ore-bodies have formed in spaces of multiple fissuring, where the belt of master-fissures cuts through lime-beds, broken and rifted in different directions by the complex intersection of sheeted belts, due to cross-fissures and to diagonal fissures.

The ores of primary formation are mostly deposited by replacement of the limestone. Quartz occurs in many varied

forms,—from massive limestone, more or less completely altered to quartz, with little change in structure, to the white, crystalline mineral, grading insensibly into soft, crumbling, pulverulent quartz, in appearance resembling granulated sugar.

In certain places in these mines the limestone appears to have been sheeted and broken into large, thin and sharp fragments before it was replaced by the ore; the sharp edges of the pieces of limestone were not rounded in the conversion; there has not been any solution of the rock without the perfect pseudomorphic replacement of its structure by the minerals.

This has occurred not only in the replacement of the limestone by quartz, but also in its replacement by massive argentiferous galena, as fine-grained in its crystalline structure as steel. The galena reproduces the shape of the original limestone fragments, so that they are fossilized by lead-sulphide, as wood is petrified by the infiltration of silica, only less perfectly.

The largest body of galena of this character occurred in the Uncle Sam mine. The ore-body, 50 ft. long, 13 to 20 ft. wide, and 50 to 60 ft. high, was formed entirely of pure lead-sulphide, with no other minerals except calcite and the lime wall-rock. The ore averaged 75 per cent. of lead and 50 oz. of silver per ton. In this ore-body the massive limestone, prior to its mineralization, had been fractured vertically in large, sheeted fragments, some of which would measure 10 to 15 ft. long and 10 to 25 ft. high, but only 6 to 15 in. thick. Even the largest masses of rock were altered throughout to steel-galena. Numerous vertical open seams and fractures, from the thickness of a knife-blade to 2 in. in width, separated these irregular sheets of ore one from another. A vertical fracture, 12 to 18 in. wide, passed through the ore-body; it was more recent in formation than the primary ore and was filled with coarsely crystalline galena, with cleavage faces 2 to 3 inches across, deposited by crystallization.

In general, in the mines on Godiva mountain, fine-grained galena, replacing the limestone, is of primary origin, while coarsely crystalline galena is usually secondary; although some of the lead-ore deposited by crystallization (or crustification) appears to be primary.

Review of the Phenomena of the Deposition of Ores in Limestone. —A study should be made of the structure of the ore-bearing limestones, with the special object of determining the causes that have made certain strata favorable for ore, while other beds in the same geological formation, having an almost identical chemical composition, and so situated that they are traversed by the same fissures, through which the mineral-depositing waters have been introduced, have remained barren. In many instances the productive and the barren strata are interbedded and so situated that the ore-bearing fissures cut through all the beds alike, without any change in this selective deposition of the ores.

Analyses of these ore-producing limestones are needed to determine the amount and character of the carbonaceous substances present, and also the minute traces of other elements, some of which may be found to have had an influence on the formation of the deposits. That such an influence may have been exerted seems probable, when we consider the enormous masses of the highly soluble limestones that have been dissolved or replaced in the creation of the ore-bodies. It has been shown, for example, that the small percentage of bitumen or other hydrocarbon contained in the rock, and set free by its dissolution, has strongly aided in the deposition of the ore.

Prof. Church, discussing the deposition of ores in limestone, says: "The operation of solutions whose composition we do not know can be judged only by their effects. When metasomatic replacement takes place in limestone, it is generally assumed that lime-carbonate goes into solution, while its place is taken by the ore-substances,—that is to say, that the action is molecular substitution, and not atomic; but it is conceivable that the change should begin by an interchange of acidic elements—that SiO_2 should drive out CO_2. Subsequent changes might remove the lime-silicate by another process of substitution, since it is more soluble than silica;* but the point is that CO_2 would be liberated, and, though the original ore-solution were free from CO_2, it would immediately become charged

* In the Tintic mines, lime-silicate does not appear to have been formed; the silica directly replacing the lime-carbonate, or the carbonate of lime and magnesia, as the case may be.

with that agent and exert the well-known dissolving power of carbonic acid solutions. In this way a solution which would have but feeble power in other rocks may in limestone set up a chain of reactions that would intensify its effects. . . . Limestone contains the elements for self-destruction, since the breaking-up of one lime-carbonate molecule may cause the solution of another; and as this cannot be said of any other rock, we reach a possible explanation of the comparative frequency of ore-bodies in limestone. The dolomites would, of course, present similar reactions." Prof. Church continues, respecting "The selection of a favored stratum for ore-deposition. In some situations the solutions, before reaching the stratum of actual ore-deposition, must have passed several strata suitable for their action, if they had possessed from the beginning the power of solution which they showed ultimately. . . . Ore-solutions exhibit a selective power which is extraordinary in a water fully supplied with dissolving qualities, but quite explicable in a solution which lacks this power."*

Many contributory causes have in all probability co-operated in the deposition of the ore, such as decrease of pressure and reduction in the temperature of the solutions, the mingling of mineral-bearing waters of different chemical composition entering the limestone formation through distinct fissured belts, etc.; but the important factor appears to have been the great solubility of these limestones and dolomites in the waters which brought in the minerals, joined with the chemical activity of the contained hydrocarbons released in the dissolution of the rock.

In the solution of the limestone, the incidental liberation of large volumes of carbonic acid, ever dissolving more and more of the rock, set free a constantly renewed supply of carbonaceous matter, whose function was to remove all free oxygen and reduce the sulphates in the waters to sulphides. At the same time, the calcium- and magnesium-carbonates, when dissolved, neutralized the acids and destroyed the chemical equilibrium, so that the mineral-saturated waters could no longer hold the metals in solution, after the addition of the elements derived from the limestone. The combined action of

* *Genesis of Ore-Deposits*, pp. 196, 197. *Trans.*, vol. xxiii., 595, 596.

the carbon, hydrogen, lime and magnesia contained in the rock was to deoxidize the solutions and bring them to the "critical-point," when deposition of the ores rapidly took place.

In conclusion: The ores of primary formation in the Tintic mines have been, in most of the occurrences, deposited from highly heated solutions by the metasomatic replacement of the limestone; only in relatively subordinate amount have the metallic sulphides been formed by crystalline growth in the rock, or by crystallization in the interspaces of the ore-bodies.

In the instance cited, in the Uncle Sam mine,* in the large body of steel-galena, without quartz, replacing the fractured lime strata, the deposition seems to have been from solutions either free from silica, or more probably of so low a temperature that the chemical reaction in the substitution of quartz for the lime-carbonate could not take place.

In Tintic, the limestones, when unaltered, retain the included carbonaceous matter deposited with the sediments. In the ore-bodies, all forms of the hydrocarbons have been destroyed, either in the primary formation of the minerals or in the subsequent oxidation; the deepest mines in the district (1700 and 2100 ft., vertical depth) not having reached ground-water level.

Whatever may have been the *rôle* of the volatile hydrocarbons in the original creation of the deposits, no evidence has been found of their ever having been present. Tintic district has been a center of intense volcanic activity, and it seems almost inevitable that, with the presence of notable quantities of bituminous matter in the rocks, volatile hydrocarbons would have been formed.

Many examples might be given of limestones, especially of magnesian limestones, which carry more or less organic matter and constitute the favored geological formations in the selective deposition of the ore. The zinc- and lead-deposits of Missouri and the lead- and copper-ores of Tintic District, Utah, carrying silver and gold, were chosen, owing to the author's more detailed acquaintance with the ore-deposits of those regions.

* See *ante*, p. 340.

Petroleum.

The occurrence of petroleum in the Redington quicksilver-mine, New Idria, California, is reported by Luther Wagoner.* He says: "Mineral-oil occurs in considerable quantity, a barrel of forty gallons being collected in one drift. It was used for lubrication of the machinery."

Prof. Egleston, writing of the quicksilver-mines in northern California, says: "At the Rattlesnake mine, near Pine Flat, where large quantities of metallic mercury are found, the rock contains so much petroleum that it has been necessary to make special arrangements to burn the carbides of hydrogen, since the distillation of the petroleum causes an extra quantity of poor soot to be formed in the condensation-chambers."†

At the zinc- and lead-mines near Shullsburg, Wisconsin, thin partings or beds of brown shale, highly charged with petroleum, are found in the Trenton limestone. Prof. Blake, discussing the peculiar occurrence of this shale, known as the "oil-rock," says: "We find that this petroleum-shale, this horizon of hydrocarbons, is to-day the chief lower horizon of deposition of the lead- and zinc-ores. Certainly, if this shale did not influence or determine the original primary accumulation of the ores, it appears to have exerted a very important influence upon the secondary or later deposition, from solutions percolating downwards."‡

In the mines at Silver Reef, Utah, an oily substance, supposed to be petroleum, is reported to have occurred in the refractory ores at water-level.§

Rudolf Keck notes the association of organic matter with ore-deposits. He says: "Organic matter occurs in the state of asphaltum in the cinnabar mines in the Bavarian Palatinate; in that of petroleum, in the mines of California, Nevada and Hungary; in that of anthracite and graphite, in mines in Transylvania, Portugal, Derbyshire, Calcutta, Saxony, Baden, etc."‖

* "The Geology of the Quicksilver-Mines of California," by Luther Wagoner. *Eng. and Min. Jour.*, vol. xxxiv., p. 334.

† "Notes on the Treatment of Mercury in North California," by T. Egleston, *Trans.*, iii., 273.

‡ William P. Blake, Discussion of the "Lead- and Zinc-Deposits of the Mississippi Valley," *Trans.*, xxii., 631.

§ See *ante*, pp. 322–327.

‖ "The Genesis of Ore-Deposits," by Rudolf Keck, *Eng. and Min. Jour.*, vol. xxxv., p. 3.

Bitumen.

The occurrence of bitumen, and its influence in the formation of the zinc- and lead-deposits in the Cherokee limestone, in Southwest Missouri, has already been discussed.*

Becker notes the existence of bitumen in the Manhattan, Knoxville, Phœnix, Oathill, Manzanita, Great Western and Great Eastern quicksilver-mines, and also at Sulphur Bank, California. At the Phœnix mine, a peculiar non-oxygenated hydrocarbon (napalite), with 90 per cent. of carbon and 10 per cent. of hydrogen, occurs quite abundantly.†

Luther Wagoner, in an article on the geology of the quicksilver-mines of California, says: "Oil (petroleum), more or less oxidized, is observed in all mines of quicksilver on this coast, and in general is found as bitumen or a thick tar."‡

Prof. Christy thus describes the occurrence of bitumen at New Almaden, Cal.: "The ore at New Almaden is cinnabar. Native quicksilver occurs also; but, as a rule, in small quantities only. Pyrite occasionally accompanies the ore. Bitumen is quite common, sometimes as a fragile, black, lustrous solid, resembling soft bituminous coal, but melting easily, like tar; at other times it occurs in the vugs of the gangue, in a liquid state, like coal-tar. I have found lumps of apparently pure cinnabar from the New Almaden to give a voluminous residue of pulverulent charcoal, when subjected to sublimation out of contact with the air. This would seem to show that the bituminous substance is intimately associated with the cinnabar."§

Marsh-Gas (CH_4).

In the quicksilver-mines of California marsh-gas was discovered by Becker. In the Phœnix mine, on the 150- and 300-ft. levels, inflammable gas, mainly composed of marsh-gas, issues from cracks in the rock.‖ At Sulphur Bank, California, 79

* See *ante*, pp. 305, 306.

† "Geology of the Quicksilver-Deposits of the Pacific Slope," by Geo. F. Becker, *U. S. Geol. Surv.*, Monograph xiii., pp. 371, 372.

‡ "The Geology of the Quicksilver-Mines of California," by Luther Wagoner, *Eng. and Min. Jour.*, vol. xxxiv., p. 334.

§ "Quicksilver-Reduction at New Almaden," by Samuel B. Christy, *Trans.*, xiii., 547–548.

‖ "Geology of the Quicksilver-Deposits of the Pacific Slope," by George F. Becker, p. 373.

parts of marsh-gas were found in 1000 parts of the gases escaping with the ore-depositing waters.*

Flows of gas under heavy pressure were struck in the deeper levels of the Silver-Islet mine, Lake Superior. Subsequently, in extending the levels, vugs and cavities in the vein were found, lined with crystals of galena and calcite, in which the gas had probably been stored. In sinking the shaft, gas was also encountered in the slate, and it appears to have pervaded the country-rock below the 8th level (440 ft., vertical depth). The gas was associated with small flows of strong, acrid mineral-water, carrying much calcium chloride. It burned with a purple, blue, or yellowish flame, and was supposed to be light carburetted hydrogen, but it was never analyzed.†

Small quantities of hydrocarbon-gas are stated by Mr. B. Tibbey to have been struck in following the vein on the 300-ft. level of the Illinois mine, Walkerville, Butte City, Montana. The gas burned with a bright-yellow flame, like ordinary illuminating gas. This occurrence is remarkable, as the vein occurs in granite.

Review of the Action of Volatile Hydrocarbons.—In the Joplin, Mo., mines, the greater part of the bitumen set free by the extensive subterraneous erosion of the lime strata is still preserved in the ore-bodies below water-level, owing to the primary deposition having been effected by mineral-solutions of normal temperature. The same is also true of the petroleum occurring with the zinc-ore in the oil-rock in the Trenton limestone in Wisconsin, to which reference has been made. But in many ore-deposits in other mining-regions the heat accompanying the deposition has been so great, and the chemical activities so intense, that every trace of volatile hydrocarbons has been destroyed.

Petroleum contained in the strata may be decomposed by (1) destructive distillation, due to the earth-temperatures or to the heat of the ascending mineral-solutions; (2) by oxidation, the carbon and hydrogen forming carbon-dioxide and water; and (3) by the action of sulphur, which dehydrogenizes the oil.

* *Ibid.*, p. 258.

† "The Silver-Islet Mine and Its Present Development," by Francis A. Lowe, *Eng. and Min. Jour.*, vol. xxxiv., pp. 320-323. See also *ante*, p. 313.

Petroleum and similar hydrocarbons, when heated and subjected to the action of sulphur at temperatures (in the case of the heavier oils) far below that at which distillation occurs, are rapidly decomposed, with formation of sulphuretted hydrogen and of oils with a greater proportion of carbon than the original oil; or, if the sulphur be in excess, carbon is in some instances deposited.

The *rôle* of the volatile hydrocarbons in the primary formation of mineral-deposits, especially where the deposition is due to igneous disturbances, has not received the attention it deserves. Investigation is needed of the action that marsh-gas and other hydrocarbon-gases exert in the deposition of ores; particularly in the formation of deposits of cinnabar, which are frequently associated with bituminous shale, bitumen and volatile hydrocarbons.

Marsh-gas has a theoretic reducing power one-half that of hydrogen and fifty per cent. greater than that of pure carbon. In the formation of ore-deposits, directly induced by igneous action, temperatures must inevitably occur in the depths of the strata, such that gaseous hydrocarbons would act with great energy in the deoxidation and precipitation of the metals. Under like conditions, petroleum, and the volatile carbon compounds with high boiling-points, would exert a reducing power but little inferior, and, from the high specific gravity of their vapor, would displace steam and all other gases of less relative weight.

VIII. The Relative Reducing Power of Minerals.

Calculation of the Theoretic Reducing Powers of Various Organic and Inorganic Mineral Substances usually Occurring in Association with Ore-Deposits, Based upon the Weight of Oxygen Consumed.

The quantitative value, or amount of work accomplished in the formation of ore-deposits by the various reducing substances, is measured by the weight of oxygen with which they unite. This work of deoxidation may be termed the "*duty*" of the reducing agent.

In calculating this duty for the more common organic and inorganic minerals which occur in ore-bodies or in strata in which ores were formed, or into which they were intro-

duced by the waters, either in the original deposition or in the secondary enrichment of the deposits, it has been found more convenient to make the values relative, assuming hydrogen, the most powerful deoxidizing agent, to have a value of 100.

Let R represent the relative reducing power, or duty, of any mineral substance.

Q be the weight of oxygen consumed by one part of the mineral.

S be the weight of the mineral required to unite with one part of oxygen.

P be the weight of hydrogen which combines with 100 parts of oxygen.

The value of Q may be determined in each case from the chemical reactions which take place.

Thus, for hydrogen,

$$2H + O = H_2O,$$
$$2 + 16 = 18,$$

whence, by proportion, the weight of oxygen consumed by 1 part of hydrogen is determined.

$$2 : 16 :: 1 : Q = 8.00.$$

R has been assumed for hydrogen as 100.

In the case of carbon, the reaction is

$$C + O_2 = CO_2,$$
$$12 + 32 = 44,$$

whence, $12 : 32 :: 1 : Q = 2.6666$.

The relative power, or duty, of carbon compared with hydrogen is

$$8 : 2.6666 :: 100 : R = 33.33.$$

For oxygen the value of P is determined from the weight of hydrogen that unites with one atom of oxygen:

$$O + 2H = H_2O,$$
$$16 : 2 :: 100 : P = 12.5.$$

P is a constant and always a minus quantity; the oxygen combined with a mineral substance diminishing its reducing power.

R, Q and S are determinable by the following formulas:

$$R=\frac{100\,Q}{8},\qquad Q=\frac{8\,R}{100},\qquad S=\frac{1}{Q};$$

whence, by substitution,

$$S=\frac{1}{Q}=\frac{1}{\frac{8\,R}{100}}=\frac{12.5}{R},\qquad Q=\frac{1}{S},\qquad R=\frac{12.5}{S}.$$

From the above it is seen that in assuming, for convenience, the value of R for hydrogen as 100, it was equivalent to multiplying the corresponding value of Q (= 8) by 12.5. Consequently the several values of R, being calculated for equal weights of the mineral substances, are in each instance the weight of oxygen which is consumed by 12.5 parts of the reducing agent. Thus, 12.5 parts of carbon consume 33.33 parts of oxygen, etc.

The "duty" of any compound substance is the sum of the reducing powers of the elements of which it is composed. Thus, for the hydrocarbons:

Let a = the percentage of carbon,
b = " " " hydrogen,
c = " " " oxygen.

Then $R = (33.33\,a + 100\,b) - 12.5\,c$.

By a formula of this kind R can be calculated directly from the percentage-composition of any substance. Even in the complex metallic sulphides, arsenides, etc., R may be calculated from the composition by substituting in the formula the value of R for sulphur, arsenic, etc.

For carbon-monoxide the value of R may be calculated from the percentage-composition: carbon, 42.86; oxygen, 57.14.

$$\begin{aligned} 0.4286 \times 33.33 &= 14.28 \\ \text{Less } 0.5714 \times 12.5 &= 7.14 \\ &\hline \\ 7.14 &= R. \end{aligned}$$

Or from the equations and proportions:

$$CO + O = CO_2,$$
$$28 + 16 = 44.$$
$$28 : 16 :: 1 : Q = 0.5714,$$
$$8 : 0.5714 :: 100 : R = 7.14.$$

Marsh-Gas, CH_4.—Marsh-gas (methane) belongs to the paraffin series of volatile hydrocarbons; its composition is

Carbon,	75.00
Hydrogen,	25.00
	100.00

By oxidation, marsh-gas forms carbonic acid and water, thus:

$$CH_4 + O_4 = H_2CO_3 + H_2O.$$

$$16 : 64 :: \quad 1 : Q = \quad 4.00.$$
$$8 : \quad 4 :: 100 : R = 50.00.$$

Or, calculated from the composition,

$$33.33 \times 0.75 = 25.00.$$
$$100.00 \times 0.25 = 25.00.$$
$$50.00 = R.$$

Petroleum.—American petroleum is in great part a mixture of hydrocarbon oils of the paraffin series, represented by the formula C_nH_{2n+2}. The heavier oils average, approximately, carbon, 85 per cent.; hydrogen, 15 per cent.; corresponding very nearly to the formula, $C_{16}H_{34}$. Assuming that the carbon is completely oxidized to carbonic acid, and the excess of hydrogen to water:

$$C_{16}H_{34} + O_{49} = 16H_2CO_3 + H_2O,$$

from which $R = 43.36$.

Bitumen.—With bitumen is included mineral-tar, maltha, and the solid oxygenated hydrocarbons, such as grahamite. Their composition, while variable, usually falls within the limits of the analyses No. 1 and No. 2:

	No. 1.	No. 2.	No. 3.
Carbon,	80.00	89.00	81.00
Hydrogen,	14.00	11.00	10.00
Oxygen,	6.00	0.00	9.00
	100.00	100.00	100.00

The value of R for analysis No. 1 = 39.92, and for analysis No. 2 = 40.67. Analysis No. 3, of grahamite (gilsonite), with but 10 per cent. of hydrogen, gives a value for R of 35.88. In the above analyses it is probable that some nitrogen and sulphur are included with the oxygen, so that the deduction made for oxygen is slightly too great.

Bituminous Coal.—The average composition of bituminous coal may be stated as falling within the limits of the analyses 1 and 2:

	No. 1.	No. 2.
Carbon,	81.00	88.00
Hydrogen,	4.00	7.00
Oxygen,	15.00	5.00
	100.00	100.00

The duty calculated from the composition in the above analyses is, for coal No. 1, $R = 29.13$; and for coal No. 2, $R = 35.71$.

Lignite.—The composition of lignite is extremely variable and is much affected by the amount of decomposition it has undergone. Assuming that the analyses given below represent the ordinary limits of composition, the value of R for lignite No. 1 is 19.50, and for No. 2, 28.83.

	No. 1.	No. 2.
Carbon,	60.00	73.00
Hydrogen,	4.00	7.00
Oxygen,	36.00	20.00
	100.00	100.00

Native Humus Acid.—Dana gives the composition of humus acid from Bohemian brown-coal as $C_{46}H_{46}O_{23}$, which corresponds to:

Carbon,	55.31
Hydrogen,	4.61
Oxygen,	40.08
	100.00

$$998 : 1440 :: 1 : Q = 1.4428.$$
$$8 : 1.4428 :: 100 : R = 18.04.$$

Or, calculated from the composition,

$$0.5531 \times 33.33 = 18.44$$
$$0.0461 \times 100.00 = 4.61$$
$$23.05$$
$$\text{Less } 0.4008 \times 12.5 = 5.01$$
$$18.04 = R.$$

Sulphur.—Sulphur in ore-deposits may oxidize under certain conditions to sulphurous acid, but usually sulphuric acid is formed.

$$S + O_2 = SO_2;\ \text{whence,}\quad R = 12.50$$

$$S + O_3 = SO_3;\ \text{whence,}\begin{cases} R = 18.75 \\ Q = 1.50 \\ S = 0.667. \end{cases}$$

Combined sulphur may, for convenience in calculating the duty of sulphides, be regarded as oxidizing to SO_4; as if all the oxygen combined with the sulphur and none with the base, giving the values $R = 25.00$; $Q = 2.00$; $S = 0.50$.

Sulphuretted Hydrogen.—The complete oxidation of sulphuretted hydrogen forms sulphuric acid, $H_2S + O_4 = H_2SO_4$, from which $R = 23.53$. When oxygen is deficient, water is formed, with separation of sulphur. The reaction then is:

$$H_2S + O = S + H_2O;\ \text{whence,}\ R = 5.88.$$

Pyrite and Marcasite.—Three distinct reactions may occur in the oxidation of pyrite and marcasite (FeS_2):

(1) With liberation of sulphur, and formation of ferrous-sulphate—

$$FeS_2 + O_4 = S + FeSO_4;\ \text{whence,}\ R = 6.67;\ Q = 0.533;\ S = 1.876.$$

(2) With formation of ferrous sulphate and free sulphuric acid, one atom of sulphur may be regarded as oxidizing to SO_3, the other to SO_4—

$$FeS_2 + O_7 + H_2O = FeSO_4 + H_2SO_4;\ \text{whence,}\ R = 11.67;\ Q = 0.933;\ S = 1.072.$$

(3) When the oxidation of pyrite takes place with excess of air, ferrous sulphate is first formed, and by a complicated series of reactions, with further absorption of oxygen, the final result is the formation of limonite and sulphuric acid. The equation may be written:

$$4FeS_2 + O_{30} + 11H_2O = 2Fe_2O_3,3H_2O + 8H_2SO_4,$$

Giving $R = 12.50$; $Q = 1.00$; $S = 1.00$.

In the substitution of blende and galena for pyrite in secondary deposition, the reactions corresponding to equation (1) may be expressed:

$$FeS_2 + ZnSO_4 = ZnS + FeSO_4 + S.$$
$$FeS_2 + PbSO_4 = PbS + FeSO_4 + S.$$

Pyrite also deoxidizes sulphuric acid, with the formation of sulphuretted hydrogen and sulphur:

$$FeS_2 + H_2SO_4 = H_2S + S + FeSO_4.$$

The reduction of zinc- and lead-sulphate and lead-carbonate by pyrite is shown by the following equations, corresponding to equation (2):

$$FeS_2 + ZnSO_4 + H_2O + O_3 = ZnS + FeSO_4 + H_2SO_4.$$
$$FeS_2 + PbSO_4 + H_2O + O_3 = PbS + FeSO_4 + H_2SO_4.$$
$$FeS_2 + PbCO_3 + H_2O + O_3 = PbS + FeSO_4 + H_2CO_3.$$

In the presence of an excess of air, reactions, corresponding to equation (3), take place in the reduction of these soluble salts of zinc and lead, as follows:

$$4FeS_2 + ZnSO_4 + 11H_2O + O_{26} = ZnS + 2Fe_2O_3,3H_2O + 8H_2SO_4.$$
$$4FeS_2 + PbSO_4 + 11H_2O + O_{26} = PbS + 2Fe_2O_3,3H_2O + 8H_2SO_4.$$
$$4FeS_2 + PbCO_3 + 11H_2O + O_{26} = PbS + 2Fe_2O_3,3H_2O + H_2CO_3 + 7H_2SO_4.$$

Arsenic and Antimony.—The values of R for arsenic and antimony are obtained from the following equations:

$$2As + O_5 = As_2O_5; \text{ whence, } R = 6.67.$$
$$2Sb + O_3 = Sb_2O_3; \text{ whence, } R = 2.50.$$

Arsenopyrite.—The composition of arsenopyrite, FeAsS, is as follows:

Iron,	34.30
Arsenic,	46.00
Sulphur,	19.70
	100.00

The value of R may be calculated either from the reaction, the arsenic oxidizing to As_2O_5, or from the composition, as follows:

$$2FeAsS + O_{13} = As_2O_5 + 2FeSO_4.$$

$$326 : \quad 208 :: 1 \quad : Q = 0.638.$$
$$8 : \quad 0.638 :: 100 : R = 7.98.$$
$$0.197 \times 25 \quad = 4.92$$
$$0.46 \times 6.67 = 3.06$$
$$7.98 = R.$$

Enargite.—For enargite, Cu_3AsS_4, or $3Cu_2S, As_2S_5$, the composition and the computations are as follows:

Copper,	48.3
Arsenic,	19.1
Sulphur,	32.6
	100.0

$$3Cu_2S, As_2S_5 + 2H_2O + O_{35} = As_2O_5 + 6CuSO_4 + 2H_2SO_4.$$

One-fourth of the sulphur, or 8.15 per cent., is oxidized to SO_3, and the remainder (24.45 per cent.) to SO_4.

$$786.4 : \quad 560 :: 1 \quad : Q = 0.7121.$$
$$8 \quad : 0.7121 :: 100 : R = 8.90.$$
$$0.0815 \times 18.75 = 1.53$$
$$0.2445 \times 25.00 = 6.11$$
$$0.191 \times 6.67 = 1.27$$
$$8.91 = R.$$

Stibnite.—For stibnite, Sb_2S_3, the composition and the computations are as follows:

Antimony,	71.4
Sulphur,	28.6
	100.0

Dana gives the product of the oxidation of stibnite as valentinite, Sb_2O_3.

$$Sb_2S_3 + O_{12} + 3H_2O = Sb_2O_3 + 3H_2SO_4.$$
$$336 : \quad 192 :: 1 \quad : Q = 0.5714.$$
$$8 : \quad 0.5714 :: 100 : R = 7.15.$$

Or, calculated from the composition,

$$0.286 \times 18.75 = 5.36$$
$$0.714 \times 2.50 = 1.78$$
$$7.14 = R.$$

Pyrrhotite.—Similarly for pyrrhotite, $Fe_{11}S_{12}$:

$$Fe_{11}S_{12} + O_{47} + H_2O = 11FeSO_4 + H_2SO_4,$$
$$\text{Giving } R = 9.40;\ Q = 0.752.$$

Ferrous Sulphate.—The reactions in the case of ferrous sulphate, $FeSO_4$, are as follows:

In the oxidation of pyrite and marcasite, a mixture of ferrous sulphate and free sulphuric acid is first formed. Weed* gives the products of the further absorption of oxygen as

$$H_2SO_4, Fe(OH)_3, \text{ and } Fe_2(SO_4)_3.$$

The reaction that takes place may be written:

$$6FeSO_4 + 2H_2SO_4 + 4H_2O + O_3 = 2(H_2SO_4, Fe(OH)_3) + 2(Fe_2(SO_4)_3) + H_2O.$$

Six parts of ferrous sulphate absorb 3 parts of oxygen; or, by reduction, 2 parts of ferrous sulphate absorb 1 part of oxygen.

$$304 : 16 :: 1 : Q = 0.05263.$$
$$8 : 0.05263 :: 100 : R = 0.66.$$
$$S = 19.1.$$

Summary.

The following table of comparative reducing powers gives the quantitative value, or gross amount, of the work done by each of the deoxidizing agents. It is necessary, however, to supplement these theoretic results by observations in the field, especially of ore-deposits undergoing decomposition and reformation; and also by experimental research in the laboratory, in order to estimate accurately in each particular instance the chemical energy, or velocity with which the action takes place.

Fortunately, with respect to the greater number of the more important reducing substances commonly occurring in ore-deposits, the gravimetric power, or duty, and the chemical

* "The Enrichment of Gold- and Silver-Veins," by Walter H. Weed, *Genesis of Ore-Deposits*, p. 478; *Trans.*, xxx., 429, 430.

energy run nearly parallel; so that one may be taken as the measure of the other.

The results of these calculations confirm the observations made in the zinc- and lead-mines of the Joplin, Mo., region, in the investigation of the secondary formation of the ores, of the relative order of the reducing powers of the principal deoxidizing agents, viz.: 1, bitumen; 2, bituminous coal and carbonaceous shales; 3, marcasite and pyrite; 4, blende; 5, galena.

Ferrous sulphate appears to be exceptional; notwithstanding the extreme low duty (0.66), and notwithstanding that, in forming ferric sulphate, 19.1 parts of the salt combine with only one part of oxygen, yet in the zone of oxidation, where the chemical activities have full play in the breaking-up of an ore-body, it fulfils a special mission, at once oxidizing and reducing. Its chemical energy is such that it reduces cuprous oxide to the metallic state; a change which none of the other deoxidizing agents usually found in ore-bodies are able to accomplish.* Further, its field of operation is the zone of oxidation and that border-land where the zone of oxidation merges into the zone of reduction.

This low quantitative-value is in many instances more than offset by the large amount of ferrous and ferric sulphates continuously supplied by the progressive oxidation of the pyrite in the ore-deposits. The mine-waters lixiviating the decomposing ore, although the volume of the flow may be considerable, are frequently strongly acid from the free sulphuric acid and iron sulphates held in solution.

In conclusion, the hydrocarbons, combining the highest quantitative deoxidizing power with an intense chemical activity, are the most powerful of all reducing agents. The action of the solid oxygenated hydrocarbons, bitumen, bituminous coal, and the lignitic matter finely disseminated in shales, is greatly accelerated by the facility with which these carbon-compounds, when in powder, are carried by the circulating waters into every part of the ore-bodies.

* "Enrichment of Gold- and Silver-Veins," by Walter H. Weed, *Trans.*, xxx., 431; *Genesis of Ore-Deposits*, p. 480.

TABLE.

THE RELATIVE REDUCING POWER, *R*, OR DUTY, OF EQUAL WEIGHTS OF THE ORGANIC AND INORGANIC MINERAL SUBSTANCES USUALLY OCCURRING IN THE ORE-BODIES, OR IN THE WALL-ROCK, OR INTRODUCED WITH THE CIRCULATING WATERS; HYDROGEN BEING ASSUMED AS 100.

	R.
Hydrogen (occurs combined with carbon), oxidized to H_2O,	100.00
Marsh-gas, CH_4 (carbon 75 per cent., hydrogen 25 per cent.), oxidized to $H_2CO_3+H_2O$,	50.00
Petroleum, C_nH_{2n+2} (carbon 85 per cent., hydrogen 15 per cent.),	43.36
Bitumen (carbon 89 per cent., hydrogen 11 per cent., oxygen 0 per cent.),	40.67
Bitumen (carbon 80 per cent., hydrogen 14 per cent., oxygen 6 per cent.),	39.92
Bitumen (grahamite) (carbon 81 per cent., hydrogen 10 per cent., oxygen 9 per cent.),	35.88
Bituminous Coal (carbon 88 per cent., hydrogen 7 per cent., oxygen 5 per cent.),	35.71
Bituminous Coal (carbon 81 per cent., hydrogen 4 per cent., oxygen 15 per cent.),	29.13
Carbon (graphite, etc.), oxidized to CO_2,	33.33
Carbon, oxidized to CO,	16.67
Lignite (carbon 73 per cent., hydrogen 7 per cent., oxygen 20 per cent.),	28.83
Lignite (carbon 60 per cent., hydrogen 4 per cent., oxygen 36 per cent.),	19.50
Native Humus Acid, $C_{46}H_{46}O_{25}$ (carbon 55 per cent., hydrogen 5 per cent., oxygen 40 per cent.),	18.04
Sulphur (combined), oxidized to SO_4,	25.00
Sulphur, oxidized to SO_3,	18.75
Sulphur, oxidized to SO_2,	12.50
Sulphuretted Hydrogen, H_2S, oxidized to H_2SO_4,	23.53
Sulphuretted Hydrogen, H_2S, oxidized to H_2O+S,	5.88
Pyrite and Marcasite, FeS_2 (oxidation of Fe to $2Fe_2O_3,3H_2O$; and S to SO_3)	12.50

Pyrite and Marcasite, oxidation to $FeSO_4$,	11.67
Pyrite and Marcasite, oxidation to $FeSO_4$ and S,	6.67
Pyrrhotite, $Fe_{11}S_{12}$, oxidized to $FeSO_4$ and H_2SO_4,	9.40
Enargite, Cu_3AsS_4, oxidized to As_2O_5, $CuSO_4$ and H_2SO_4,	8.90
Chalcopyrite, $CuFeS_2$, oxidized to $CuSO_4$ and $FeSO_4$,	8.72
Covellite, CuS, oxidized to $CuSO_4$,	8.39
Blende, ZnS, oxidized to $ZnSO_4$,	8.25
Arsenopyrite, FeAsS, oxidized to As_2O_5 and $FeSO_4$,	7.98
Calcium Disulphide, CaS_2, oxidized to $CaSO_4$ and S,	7.69
Stibnite, Sb_2S_3, oxidized to Sb_2O_3 and H_2SO_4,	7.15
Carbon Monoxide, CO, oxidized to CO_2,	7.14
Bornite, Cu_3FeS_3, oxidized to Cu_2SO_4, $CuSO_4$ and $FeSO_4$,	7.01
Arsenic, oxidized to As_2O_5,	6.67
Tetrahedrite, $4Cu_2S.Sb_2S_3$, oxidized to Cu_2SO_4, $CuSO_4$ and Sb_2O_3,	6.39
Iron, oxidized to Fe_2O_3,	5.36
Iron, oxidized to Fe_3O_4,	4.76
Iron, oxidized to FeO,	3.58
Chalcocite, Cu_2S, oxidized to Cu_2SO_4,	5.04
Galena, PbS, oxidized to $PbSO_4$,	3.35
Tellurium, oxidized to TeO_2,	3.20
Copper, oxidized to CuO,	3.15
Copper, oxidized to Cu_2O,	1.58
Antimony, oxidized to Sb_2O_3,	2.50
Rhodochrosite, $MnCO_3$, oxidized to MnO_2,	1.75
Siderite, $FeCO_3$, oxidized to Fe_2O_3,	0.86
Ferrous Sulphate, $FeSO_4$, oxidized to $Fe_2(SO_4)_3$,	0.66
Magnetite, Fe_3O_4, oxidized to Fe_2O_3,	0.46

Discussion.

(*Trans.*, xxxiii., 1065.)

John A. Church, New York, N. Y.: Professor Jenney has performed a notable service in presenting this summary of the steadily increasing body of observation on the presence of carbon in rocks of all kinds and its probable influence upon ore-deposition, and in formulating a mode of comparing directly the relative resistance of minerals to oxidation, as well as their reducing-power, and the protective action which minerals having higher reducing-powers exert in preventing the oxidation of associated minerals which possess relatively lower affinities for oxygen.

I have had an opportunity of observing a vein which falls within the scope of his interesting discussion. The vein at Ku Shiau Tzu, Mongolia, lies directly across a contact of limestone and overlying bituminous shales. Probably it occupies a compression-fissure. The shale has been reduced to such a condition of non-coherence that much of it can be crushed in the hand, producing a handful of angular fragments resembling beech-nuts in shape and size.

In the limestone the metals are principally in argentiferous galena with some pyrite and blende; but the latter two are very subordinate in quantity to the galena. In short, it is an every-day lead-vein in limestone, with siliceous limestone gangue. It is one of those veins in which the ore is not continuous, but consists of a band in the country-rock in which seams of lead sulphide begin at one wall and cross in a bent form, increasing in thickness, to the other wall, where they thin out and end. This may indicate torsional stress, but the shape of the lenses points to some other action. They often ran nearly parallel to the hanging-wall for a considerable distance and crossed the vein on a moderate angle, but turned sharply along the vein on approaching the foot-wall. The intermediate rock contains nodules, bunches and specks of ore, and the lenses vary exceedingly in size, shape and position in the vein.

In the bituminous shale the deposition of ore is not at all like that in the limestone. The minerals in the shale are tetrahedrite and native silver, the latter occurring in fine scales and sheets of pure metal, weighing from 50 to possibly 100 oz. I cannot speak of these larger sheets from much acquaintance,

for all but one of them were stolen by the miners, but the metallic silver in scales and sheets was an important part of the ore.

It is necessary to exclude the notion of secondary deposition at Ku Shau Tzu, because the influence of the shale with its superabundant store of powerful reducing-agent should have gathered to itself every metal taken into solution by descending surface-waters. Whether that was the case immediately at the surface I do not know, as the mine was an old one when I first saw it. The absence of galena, blende and pyrite from the shale, at depths of 300 and 400 ft., indicates that secondary deposition, if present at any time, did not reach so far; and this was to be expected from the reducing-power of the shale at the surface.

I considered that the conditions indicated deposition from a solution rising through the limestone first and afterward through the shale which once covered the lime-rock, though now it is tilted and partially eroded. The limestone precipitated what it could, and the abundant store of carbon in the shale perhaps took the last traces of metal. But this explanation is not without its difficulties when applied to the limestone, however confident we may be of the reducing-powers of the shale.

The feeble reducing-power to which galena yields—only 3.35 per cent. of H, according to Prof. Jenney—explains its presence in the limestone well enough, but why should this rock precipitate also blende (8.25 per cent.) and pyrite (11.67 per cent.), while it left tetrahedrite (6.39 per cent.) to the shale? The reduction of metallic silver in the shale is, of course, not surprising.

There must have been some other selective agency than mere position or the chemical energy of carbon at work to produce these effects. The same considerations lead us to doubt that there was an interchange of elements between different parts of the ascending column of mineral solution, by which the complete precipitation of any mineral in one rock, the shale, for instance, would so dilute the mother-liquor there that this mineral would pass by diffusion from the solution going through the limestone to that in the shale. Such action is familiar in chemical work. When a drop of reagent causes partial precip-

itation, the remainder of the dissolved substance is diffused immediately through the whole body of liquid. This could not have taken place at Ku Shau Tzu without producing more abundant deposition in one of the rocks than in the other, according to its precipitating energy, and the phenomenon there is not quantitative, but selective, concentration. The quantity of mineral was greatest in the limestone.

It is conceivable that the deposition of ore in the shale would liberate carbon, which, going into solution, might reach the limestone and there act upon the advancing ore-solution, thus giving the shale a large radius of action, and making it contribute to deposition in the neighboring rock.

This question of interchange of elements between solutions, or diffusion, is of great interest and importance, and though it is not germane to the subject of Prof. Jenney's paper, I may be permitted to point out that some observations indicate that there is no horizontal diffusion or exchange of dissolved substances between the two halves or ends of the moving column of solution, which we may consider conveniently to have the same length as the vein. There is evidence that the solution from which an ore of general average composition is deposited may produce ore-bodies that vary in their different parts in a manner important to the miner if not to Nature.

In the well-known case of the Crown Point-Belcher bonanza, one-half of the ore-body contained more gold in proportion to silver than the other half, and the difference was not fortuitous, but persisted through the whole extent of the bonanza. The country-rock was eruptive, the mass of the deposit was silica, the total length was only 500 ft., and it is difficult to see how there could have been selective deposition from a uniform solution. Granting that the difference began at the point where the solution was formed, this difference in the two halves of the current must have been preserved throughout its wanderings,—a proof that there were no exchanges between the two halves.

Of course, if lateral secretion in its first and most restricted sense were true, and the ore were derived from the immediate walls of the vein, an explanation might be found. This extremely limited conception is, I believe, entirely abandoned; and the persistent difference of the Crown Point-Belcher solu-

tion along adjacent vertical and, perhaps, horizontal lines of travel, possibly to great distances, is an unexplained phenomenon. Other cases are known in which the facts indicate that there was no exchange of elements between the parts of the common solution from which the respective ends of the ore-body were formed.

It is not probable that the north and south ends of the Crown Point-Belcher ore-body differ in date, for the mass was decidedly lenticular, very thick in the middle and thinning out in all directions. The natural conclusion is that the action, being a replacement of country-rock, began in the central portion of the mass, and the greater thickness there is the effect of longer action. This is equivalent to saying that the action was continuous over the whole of the steadily increasing vein-area, and that ore was forming in the center while it was forming at both ends.

Occurrences of this kind have an obvious bearing upon the views which Prof. Van Hise has expressed upon the movement of waters in the rocks. A natural explanation of the Crown Point-Belcher case is that the thin-leaved porphyry of the Comstock offered a means of ready flow which operated as a channel, to which waters from widely different sources of origin were directed; but this only emphasizes the fact that the two currents maintained their individuality through long wanderings, and even when joined in a channel of limited section. It also implies that gold and silver can be picked up anywhere in the middle of the earth, a conclusion which cannot be admitted; for it is probable that the solution of metals is as selective and phenomenal as is their deposition.

Differential deposition, as in this case, necessarily brings up the question of electro-chemical action; but which way would it work, for or against differentiation? My impression is that it would act for uniformity, and there is no evidence that electrical action in the rocks is strong enough to move a metal or salt through 500 ft. of minute channels.

Prof. Jenney's description of the ore-deposition in the Tintic limestones may be accepted as accurate for the galena of the celebrated "Emma" mine, in Little Cottonwood Canyon, Utah. I well remember a large mass of galena there, almost pure in the center, and surrounded by a thick mass consisting of de-

composed limestone fragments in galena, graduating to enclosures of galena in limestone as the distance from the center increased, and ending with scattered, small impregnations of galena in the nearly unaltered limestone walls. The angular shape of the inclusions mentioned by Prof. Jenney was noteworthy there also.

Every mining engineer will recall from his own experience occurrences which sustain the general position which Prof. Jenney takes in reference to the presence of carbon in the rocks of mining districts. One of the problems at Tombstone which the new owners are attacking with such faith is the future of the Contention vein, where it passes through the Lucky Cuss limestone, which is strongly fetid for 100 or 200 ft. in thickness. It may be years before it is reached, but it presents the elements for active chemical exchanges. When I was a superintendent in Tombstone, two of my men, who were mining manganese in the higher strata of this limestone, nearly lost their lives by an effusion of CO_2 into a shallow, open pit where they were working. The gas accumulated during the night and surprised them in the morning. These facts may indicate the influence of carbon in that mining district.

At the New Almaden quicksilver-mine there is an enormous discharge of carbon dioxide, which bubbles and hisses through the water in the bottom, and twice, at least, has so filled the large chambers of the old mine as to drive the whole mining-force from its work.

The *Mining and Scientific Press*, San Francisco, of May 2, 1903, has the following interesting note upon the occurrence of carbon dioxide:

"Metal mines, as well as coal mines, produce carbonic acid gas, though more rarely the inflammable 'fire damp.' In some instances the carbonic acid gas has been so abundant that the mining work has had to be abandoned. This was the case in a long drift from a deep shaft at the New Almaden, Cal., quicksilver-mine. Subsequently, an air-tight bulkhead was built in the drift, and pipes placed connecting an air-compressor at the surface with the bulkheaded drift. The intake of the compressor was attached to the pipe leading into the mine, the carbon dioxide was drawn from the mine and by means of special machinery compressed into steel cylinders under a pressure of 1,200 lb. per sq. in., in which form it was sold for the carbonating liquids. The Abbott quicksilver-mine in Lake county, Cal., makes a large amount of 'fire gas' similar to the 'fire damp' of coal mines. The occurrence of fire damp in metal mines is unusual. In the case of the Abbott mine its presence is supposed to be due to the bituminous matter in the surrounding rocks."

No. 13.

Ore-Deposits Near Igneous Contacts.

BY WALTER HARVEY WEED, WASHINGTON, D. C.

(New Haven Meeting, October, 1902. *Trans.*, xxxiii., 715.)

CONTENTS.

	PAGE
INTRODUCTION,	364
WHY ORE-DEPOSITS ARE COMMON ABOUT IGNEOUS CONTACTS,	365
OUTLINE OF A GENETIC CLASSIFICATION OF ORE-DEPOSITS,	366
Ores of Igneous Origin,	366
Igneous-Emanation Deposits,	368
Fumarolic Deposits,	368
Gas-Aqueous Deposits,	368
Deposited by Meteoric Waters,	369
CONTACT METAMORPHIC DEPOSITS,	369
Classes of Deposits,	370
Contact Zones,	371
Character of Gangue,	371
Character of Ore-Deposit,	372
Literature,	373
Geographic Distribution,	373
Copper-Deposits—Cananea Type,	374
British Columbia—Boundary District,	374
Mexico,	376
Germany,	378
Gold-Deposits,	380
Bannack Type,	381
Elkhorn,	382
Similkameen,	383
CHANGES IN ROCKS DUE TO CONTACT METAMORPHISM,	384
Changes in Mass, Volume, and Mineral Composition,	385
GENESIS OF CONTACT METAMORPHIC DEPOSITS,	387
Cause of Contact Metamorphism,	387
PERMANENCE IN DEPTH,	393
MINERAL VEINS NEAR IGNEOUS CONTACTS,	394
CONCLUSIONS,	395

INTRODUCTION.

THIS paper deals with certain ore-deposits whose structural features or mineral contents (or both) result, directly or indirectly, from igneous intrusions and their after-effects. It is largely a discussion of contact metamorphic ore-deposits based upon the physical changes in rocks due to contact action. It involves a classification of ore-deposits only so far as is abso-

lutely necessary for brevity of discussion. A genetic classification of ore-deposits is admitted to be the rational and only correct classification from a scientific point of view. To the practical miner, such a classification may be of utility if the correct discrimination of the nature and genesis of a deposit enables him to more nearly determine the probable extent and value of the deposit, and to exploit it intelligently. It is believed that the facts set forth in this paper and the explanation of them admit of such a practical use.

Why Ore-Deposits are Common about Igneous Contacts.

As is well known, the granitic rocks which adjoin contact areas are parts of great masses of igneous magma which did not reach the surface, but cooled slowly underground and consolidated into coarse-grained rocks. Subsequent uplift and denudation have exposed both the great bodies of igneous rock, and the sediments baked and altered by them, in consequence of the heat and vapors given off by the cooling magma.

Igneous contacts are ore-bearing because, (a) differentiation of the cooling magma tends to segregate the highly basic and metal-bearing portion at the border of the cooling mass; (b) pneumatolytic processes are most active about the borders of igneous masses; (c) the force of the intrusion may have shattered the adjacent rocks, forming cracks and fissures that become channels for circulating waters; (d) the shrinkage of the intrusive magma due to progressive cooling after solidification, and the shrinkage of the metamorphic zone itself, would result in the formation of fissures; and (e) as will be shown later, the porosity induced in certain sedimentary rocks by contact metamorphism (which may be compared to the burning of clay into brick) has furnished channels for circulating waters and gases, so that ore-deposition has resulted. The origin and character of the latter class of deposits is the only strictly novel feature of the paper. The deposits formed near igneous contacts by the operation of these causes have widely different characters. To discuss them a systematic arrangement is necessary, and the following provisional genetic classification has been proposed.*

* Compare *Eng. Min. Jour.*, vol. lxxv., No. 7, p. 256, Feb. 14, 1903.

OUTLINE OF A GENETIC CLASSIFICATION OF ORE-DEPOSITS.

I. Igneous (magmatic segregations).
   A. Siliceous.
   B. Basic.

II. Igneous-emanation deposits (deposited by highly heated vapors and gases in part above the critical point, *e.g.*, 365° and 200 atm. for H_2O).
   A. Contact-metamorphic deposits.
   B. Veins (closely allied to magmatic veins and to division IV.).

III. Fumarolic deposits (metallic oxides, etc., in clefts in lavas; of no commercial importance).

IV. Gas-aqueous (pneumato-hydato-genetic) deposits. Igneous, gaseous and aqueous emanations, alone or mingled with ground-waters.
   A. Filling-deposits.
   B. Replacement-deposits.

V. Deposited by meteoric waters.
   A. Underground.
   B. Surficial.

In this classification I have attempted to group the geological processes forming ore-deposits in such a way as to show genetic relations, it being understood that opinions will differ as to the class to which a particular deposit is to be assigned.

Major subdivisions are based upon magmatic segregations at one end and cold aqueous deposits at the other, with intermediate groups due to the emanations from igneous rock, the eruptive after-actions of Vogt, to which the term pneumatolytic has commonly been given; fumarolic, when these emanations issue at low temperature and pressure; gas-aqueous, in which the emanations from igneous rocks, with their burden of metals, mingle with ground-water; aqueous, in which meteoric waters alone are active, both chemically and mechanically.

Ores of Igneous Origin.

The igneous deposits are divided into basic and siliceous, the former including the deposits of iron, copper, etc., found at igneous borders and as dikes, the latter the ore-bearing pegmatites, with quartz-veins as extreme examples.

The existence of certain ore-deposits of an igneous origin seems to be fully proven and generally accepted. It is well known that the igneous magmas differentiate into siliceous and basic portions,* the resulting rocks being the siliceous aplites (alaskites) and highly basic rocks of various kinds. Where extreme differentiation has taken place, the basic residual portion contains so much iron or copper solidified as to form workable ore-deposits, constituting the subdivision B of the table. The same extreme segregation would produce the siliceous magma commonly seen as acid granites or aplites, which frequently pass into pegmatites, and the latter, in turn, into quartz-veins. These facts are well known.†

Some of these observers, however, believe that pegmatites and allied quartz-veins are due to igneous emanations of watery vapor, and are not direct segregations. Whatever may be the result of further study concerning the origin of these interesting veins, there is no doubt that in part, at least, they are of pneumatolytic origin. There is, however, abundant evidence to show that acid rocks are commonly associated with gold-deposits. Richard Beck, in his book on ore-deposits, describes the occurrence of intrusive bodies of granite near Lake Schartash which carry gold; and various observers have described dikes of similar acidic granite at Berezovsk containing quartz filling contraction-cracks, and consequently a normal constituent of the rock, which are mined for their gold values. In a treatise entitled "Criaderos Minerales de Mexico," Aguilera has given very many examples of the association of ores with extremely siliceous rocks.‡

In a general way, the laws of segregation outlined by Pirsson indicate that we should expect the siliceous segregation in the center of the igneous mass and the basic ones at the borders, while the basic dikes would traverse the igneous contacts, cutting both the igneous rock and the adjacent altered sedimentary rocks.

* Weed and Pirsson, "Shonkin Sag Laccolith," *Amer. Jour. Sci.*, July, 1901.

† Kemp, "Role of the Igneous Rocks in the Formation of Veins," *Trans.*, xxxi., p. 182; also, *Genesis of Ore-Deposits*, p. 693. Van Hise, *Trans.*, xxxi., p. 287. Lindgren, "Character and Genesis of Certain Contact-Deposits," *Trans.*, xxxi., p. 243; also, *Genesis of Ore-Deposits*, p. 733. A. W. Howitt, *Roy. Soc. Vic.*, Oct. 14, 1886.

‡ "Distribucion Geográfica y Geológico de los Criaderos Minerales de Mexico," José G. Aguilera, *Acad. Sci. Off. Secretario Fomento*, Mexico, 1901.

Igneous-Emanation Deposits.

Under this title I have grouped contact-metamorphic deposits and pneumatolytic veins. The contact-metamorphic deposits have been shown by Vogt, Lindgren, Beck and others to be formed under conditions which preclude either the presence of ordinary ground-water or steam at low temperature and pressure.

Pneumatolytic veins, of which the Cornwall tin-veins are classic examples, are admitted by most competent observers to be formed by igneous emanations proceeding from the still hot granite rocks.* The group includes part of those embraced in Vogt's "Ore-Deposits Formed by Eruptive After-Actions."

The contact-metamorphic deposits are treated at considerable length in the succeeding pages.

Fumarolic Deposits.

Under this group I have classed deposits of ferric chloride, cuprous oxide, and other metallic minerals formed in clefts of volcanic craters. Deposits of this kind have been observed by Geikie and many other geologists, and the evidence concerning them is summarized in discussing the origin of contact-metamorphic deposits. They are assigned to a separate class because they are formed at the surface of the earth under conditions which do not and cannot prevail in depth.

Gas-Aqueous Deposits.

This group is formed to include those ore-deposits formed by hot waters containing metallic salts and other substances derived wholly or in part from igneous emanations. This class of deposits corresponds closely to Vogt's igneo-aqueous or eruptive-after-action group,† but it is as well to emphasize the distinction to be made between hot waters carrying only the substances dissolved out of the rocks traversed by them and those charged with substances undoubtedly derived from igneous emanations. The evidence concerning these deposits has been very ably summed up by Suess in his recent paper.‡ Professor Suess

* *Zeitschf. Kryst. u Min.*, vol. xvi., 1890. † *Trans.*, xxxi., p. 125 *et seq.*

‡ "Ueber Heisse Quellen," *Gesel. Deutsch. Naturforscher und Arzte*, 1902.

expresses his belief in the inability of ordinary circulating waters to derive the unusual substances, such as boron, fluorine, chlorine, etc., from ordinary igneous and sedimentary rocks. In fact, Professor Suess goes further, and says, the water of the famous hot springs of the Carlsbad region is original or primitive water derived from the underlying igneous hearths and containing little, if any, meteoric water. On the other hand, there seems to be no question but that in many instances circulating meteoric waters intercept the uprising primitive waters, and the solutions thus formed deposit ores. In such cases the meteoric waters are the vehicle and not the agent. This has been concisely stated by Lindgren as follows:

"Where fissures traverse the cooling magmas, and the rocks surrounding them, it is natural that these mineralizing agents [emanations] carrying their load of heavy metals should ascend, at first under pneumatolytic conditions, above the critical temperature. Reaching the zone of circulating atmospheric waters, it is natural that they should mix with these, which probably greatly predominated in quantity. To this combination of agencies, found in the ascending waters of such regions of igneous intrusion, the formation of most metalliferous veins is probably due."*

Deposited by Meteoric Waters.

Under "Underground Deposits" I have grouped the deposits formed by circulating ground-waters in one class; those of residual origin, being leached veins, in an entirely separate class; as surficial deposits I would include *chemical* deposits of various kinds, and *mechanical* deposits, such as sedimentary rocks, placers, etc.

Believing, with Professor Kemp, that the greatest number of copper and precious-metal deposits of the world are near igneous rocks with which they are genetically connected, I hold, with Vogt, that normal terrestrial water-circulation has had a minor part in the primary origin of the deposits in question, though it may have produced later concentration from contact portions of the magmas rich in metals or from low-grade deposits of direct contact-metamorphic origin.

CONTACT METAMORPHIC DEPOSITS.

Under the title of contact metamorphic deposits I include all ore-deposits which result from the metamorphic action of

* *Genesis of Ore-Deposits*, p. 612; also, *Trans.*, xxx., p. 692.

intrusive igneous rocks upon the sedimentary rocks which they penetrate. Such deposits occur only in the zones of altered sediments about igneous intrusions; they are genetically connected with such intrusions, and are, therefore, fittingly designated as ore-deposits of contact metamorphic origin. The following subdivisions are proposed:

Deposited by Igneous Emanations.

(All classes omitted save the one under discussion.)

Contact Metamorphic Deposits.

Characterized by gangue consisting essentially of garnet, epidote, actinolite, calcite, and other lime-alumina silicates.

(a) Deposits confined to contact:

1. Magnetite deposits.
2. Chalcopyrite deposits, Kristiania type.
3. Gold-ores, Bannack type.

(b) Deposits impregnating and replacing beds of contact zone:

1. Chalcopyrite deposits—(a) Pyrrhotite ores, (b) magnetite ores, Cananea type.
2. Gold tellurium ores, Elkhorn type.
3. Arsenopyrite ores, Similkameen type.

In the present paper I shall particularly describe certain ore-deposits occurring in sedimentary rocks altered by contact metamorphism, and endeavor to show that thermal metamorphism effects certain physical changes in the sedimentary rocks of the contact-zone favorable to ore-deposition, either because the vapors and gases of the cooling magma penetrate the altered rocks and deposit metallic sulphides or by reason of a later impregnation, by circulating waters, of particular strata, *made porous by thermal metamorphism.* They, therefore, embrace both the "contact"-deposits of the Kristiania type and the types herein described, and which have been called bed-impregnations by Dalmer* and "Strikes" by Beck.† These embrace the Cananea type and the types of gold-deposits, heretofore unknown, which structurally and genetically resemble the first types mentioned, but differ in mineral contents.

* "Problems in the Geology of Ore-Deposits," *Genesis of Ore-Deposits*, p. 650; also, *Trans.*, xxxi., p. 139.

† Richard Beck, *Lehre von den Erzlagerstätten*, 1901, p. 485.

As the admirable treatise of Lindgren* presents a discussion of contact metamorphism in describing the genesis of deposits of the Kristiania type, much concerning this subject may be profitably omitted from the present paper, though it is necessary for a clear understanding of the subject to give an outline of the principal facts.

Contact Zones.

In many mining districts there occur great masses of granitic rocks, surrounded by sedimentary strata which, near the contact, exhibit marked alteration, the intensity of which diminishes as the distance from the igneous rock increases until the alteration fades out and the rocks are of normal character. Such areas are known as contact metamorphic zones, which often form a halo about igneous centers; for example, about the "stocks" of granitic rocks of the Crazy Mountains, Montana, or the batholitic masses of the Black Hills, Dakota. In other cases great areas of granitic rock, such, for example, as the great mass of granite called the Butte batholith, of Montana, which is 60 miles long and 40 miles broad, are bordered by a zone of rocks altered by contact metamorphism which may be a mile or more wide, as, for instance, near Helena, Montana. Such contact zones are often the seat of mineral deposits of great economic value, as is illustrated by the Drumlummon and other mines at Marysville, Montana; several mines at Granite and Philipsburg, Montana; the Whitlatch-Union and other mines, once productive, at Helena; the copper-mines at Clifton and Morenci, Arizona; those at Cananea, Sonora, and many other localities in Mexico. I exclude the common contact-deposits of the text-books, in which it appears probable that the igneous rock has, by its presence, localized and deflected circulating waters and thus determined the site of ore-deposition.

Character of Gangue.

Contact metamorphic deposits of whatever type are distinguished by a gangue consisting essentially of garnet, calcite, epidote, actinolite, with or without accessory wollastonite, vesu-

* "Metasomatic Processes in Fissure-Veins," *Genesis of Ore-Deposits*, p. 498; also, *Trans.*, xxx., 578.

vianite, fluorite, etc., and other minerals characteristic of contact metamorphic zones. As will be shown later, the gangue is normally a rock formed by the alteration of an impure limestone. Other rocks characteristic of contact action, such as hornfels, marble, quartzite, adinole, etc., are often present, but the ore-deposit is practically confined to the rocks resulting from the alteration of impure limestones, for reasons explained later.

Character of Ore-Deposit.

The Kristiania type of contact-deposit has already been described by Lindgren.* Specular iron and magnetite are common in true "contact"-deposits, but they occur only rarely in the deposits separated from the contact. The ore-minerals present considerable variety, and according to their metallic contents may be grouped as copper-ores and as gold-ores. A more complete classification would be, however,

(1) Chalcopyrite deposits: (a) pyrrhotitic type, (b) magnetic.
(2) Telluride deposits.
(3) Arsenopyrite deposits.

The first class includes the chalcopyrite ore-bodies carrying accessory galena at Cananea, Mexico. The subtypes are distinguished at Boundary, British Columbia. In the pyrrhotite type that mineral predominates, but the copper values are in chalcopyrite and accessory pyrite, while in the magnetite type this mineral replaces pyrrhotite. The second class is characterized by the presence of telluride of gold. In the Elkhorn example the ore-mineral is an auriferous tetradymite with associated bismuthinite. At Bannack, Mont., there is free gold, with much more abundant sylvanite. In the third class arsenopyrite occurs, carrying very high values in gold, together with free gold. The only known example of this class is the Nickel Plate mine, near Lake Okanagan, British Columbia.

The characteristic feature is the gangue of earthy silicate minerals in which the ore-minerals are disseminated. In most cases the ore-minerals and the sulphides are of simultaneous origin (or nearly so). The deposits are the direct result of the deposition of ore by the vapors and gases of the cooling magma

* "Character and Genesis of Certain Contact-Deposits," *Genesis of Ore-Deposits*, p. 716; also, *Trans.*, xxxi., 226.

(possibly, in part, the gases given off by the alteration of the sediments).

Literature.

Geologists have long recognized the peculiar characters of ore-deposits in the contact metamorphic zone about igneous intrusions, nor would it be possible for a careful observer to fail to note the successful mines and the multitude of unsuccessful prospect-pits which commonly mark such areas. It is unnecessary to go into detail on this subject, as it has been covered by Lindgren in the paper cited.* It is evident that Kemp,† although grouping contact metamorphic deposits as contact-deposits, recognized their individual character, as shown by the examples given under that head in his classification, though he gives no details of occurrence nor shows their difference from those of the Kristiania type.

Despite this very general recognition of such deposits, no discrimination was attempted until Von Groddeck defined contact-deposits of the Kristiania type, showing that they formed a distinct and separate class of ore-deposits, differing in occurrence and genesis from all other types. The contact metamorphic deposits discussed herein resemble those of this class, though excluded from it by definition,‡ as they are not *contact*-deposits, though quite as truly a result of contact metamorphism. There is a marked correspondence between the two types as regards mineral association and genesis; but the structural differences are so important, and have so marked a bearing, not alone on the theory of their genesis but, also, in the working of the deposits and a determination of their value as mines, that they merit a full discussion.

Geographic Distribution.

Ore-deposits in the zone of contact metamorphism are quite common, though in the past the more noted mines have been fissure-veins whose contents may or may not have been derived from contact metamorphic deposits. As great, massive, igne-

* "Character and Genesis of Certain Contact-Deposits," *Genesis of Ore-Deposits*, p. 716; also, *Trans.*, xxxi., 226.

† *Ore-Deposits of the United States*, 3d ed., 1902, p. 58.

‡ Lindgren, *Genesis of Ore-Deposits*, p. 717, under heading Position; also, *Trans.*, xxxi., 227.

ous intrusions are most commonly found in regions where periods of great volcanic activity have been followed by uplift and profound erosion, it is in mountainous districts that most contact metamorphic deposits occur.

No attempt will be made to discuss or describe contact-deposits of the Kristiania type. The Jimenez copper-mine, Chihuahua, Mexico,* is a typical example of this class, and the Indian Queen mine at Birch Creek, in Beaverhead county, Montana, is another example, in which later fracturing and enrichment have taken place.

Examples of the Cananea type of contact metamorphic deposits are less common, though the two noted herein are now rated among the most productive mines.

Copper-Deposits—Cananea Type.

British Columbia.—The ore-deposits of the Boundary district of British Columbia have been described by Mr. S. F. Emmons as also of contact metamorphic origin. The deposits are on Boundary Creek, near Greenwood, and comprise the workable ore-bodies of several producing mines. The ores carry 2 to 5 per cent. copper and a few dwts. of gold per ton; but as they occur in very large bodies and are metallurgically docile, they are profitably exploited. The ore-bodies occur in belts of metamorphosed limestones, 2 miles or more wide, that are adjacent to a mass of light-gray, coarsely crystalline, granitic diorite.

The ores consist of sulphides of iron and copper, associated with considerable magnetic oxide of iron, of contemporaneous formation. These minerals occur in a gangue of altered limestone consisting of amphibole, garnet, vesuvianite, zoisite, etc. Microscopic study shows that these are the result of metasomatic replacement, during which a granular limestone has been converted into an amphibolitic rock with the simultaneous development of sulphides and magnetite. From Barrell's studies† I regard it as probable that the action has been the alteration of an impure limestone by normal contact

* Weed, *Trans.*, xxxii., 396, "Notes on Certain Mines in the States of Chihuahua, Sinaloa and Sonora, Mexico."

† *Am. Journ. Sci.*, vol. xiii., April, 1902, p. 279 *et seq.*

metamorphism. This is also the view held by Dr. A. R. Ledoux.*

According to Emmons,† the ore-bodies are irregular in occurrence, and graduate insensibly in every direction, inward as well as outward, from ore into low-grade rock, the fracture-planes or walls failing to definitely enclose the ore-shoots or define their direction. In this respect they resemble the southernmost ore-bodies at Cananea, but differ from the Cananea type, in which relatively thin beds of impure limestone alternate with less congenial varieties of this rock, so that the ore-strata are fairly sharply defined. The Greenwood deposits are cut by dikes, which may be regarded as the final result of igneous action. As I stated in discussing the genesis of this class of ore-bodies, the process of metamorphism is complete before the magma solidifies; and if the sulphides were introduced during metamorphism they would be cut by the aplite and lamprophyric dikes that represent the final fissuring of the outer mass of chilled magma and filling of fissures from the molten interior.

A later and more detailed account of the ore-deposits of this district by Brock‡ gives further details, and, in part, confirms these observations of Emmons, though presenting very important additions. The ore-deposits are notable for their great size, the Mother lode ore-body being 140 feet thick and developed for 1180 feet in length and 500 feet in depth; the Knob-Ironsides lode is much larger, being 800 feet wide, proven for 800 feet in depth, and several thousand feet in outcrop. Brock distinguishes two types, a pyritic, characterized by pyrrhotite, with chalcopyrite and iron pyrites, and a magnetitic type, with magnetite and copper pyrites. Though segregated in places, the chalcopyrite is remarkably evenly distributed through the deposits. "Rarely do magnetite and pyrrhotite occur in the same deposit."§ Specular iron is found sparingly in a half-dozen properties. Occasionally marcasite, and sometimes arsenopyrite, galena, zinc-blende and molybdenite, are present. Tetrahedrite occurs in one mine and bismuthinite in another.

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* "Production of Copper in the Boundary District," *Canadian Min. Inst.*, vol. v., p. 172.

† *Genesis of Ore-Deposits*, p. 757.

‡ *Canadian Mining Institute*, vol. v., p. 365, March, 1902.

§ Brock, *Canadian Min. Inst.*, vol. v., p. 368.

The description of the gangue shows red and green garnet and epidote to be abundant in and near the veins, "and the progress of their formation may be observed in many points in all stages, not only when limestone but also when greenstone and granite form the country-rock,"* thus apparently contradicting the hypothesis that such contact minerals result only from the metamorphism of impure limestones. At the Mother lode the marmorized limestones contain the above-mentioned minerals, but the mass of the rock consists of felty actinolite. The gold values are commonly in the chalcopyrite. Magnetite and pyrrhotite, when occurring alone, are commonly almost barren, the Winnipeg pyrrhotite being an exception. There is a lack of veins and stringers enriching the main ore-body, but there appears to be an enrichment of the ore where dikes cross it. The ores are very low-grade, a representative ore carrying copper 1.95 per cent., iron 14 per cent., lime 17 per cent., silica 39 per cent., with 0.119 ozs. gold per ton and 0.44 ozs. silver.

Brock considers the ore-bodies to be composite veins "formed by mineralizing solution traversing the country-rock, principally along fissures or zones of fissures in which they deposit the economic minerals and from which they replace with their mineral contents, particle by particle, sometimes completely, the original material of the country-rock." In the same paper he says, however, that "there seems to be strong reason for supposing the deposits to be connected with eruptive after-actions."

Mexico.—The Cananea copper-deposits, which, during the last year (1901), have been so vigorously exploited that they have produced 140,000,000 lbs. of copper, are situated in the Cananea mountains, 50 miles southwest of Bisbee, Arizona, and 30 miles south of the international boundary-line. This mountain range is from 6 to 12 miles wide and 25 miles long. It rises abruptly from flat or gently-inclined prairies to a height of 8000 feet above sea-level, or 4500 feet above the plain. The range extends in a northwest and southeast direction, and it is bisected, by the low Puertecitos Pass, into two nearly equal parts. The ore-deposits occur in the southern portion of the range.

* Brock, *loc cit.* This author examined no thin sections, however.

The mountains consist of the dissected and denuded remains of an old volcano, probably of late Tertiary age. At Puertecitos Pass there is a central core of normal granite surrounded by massive andesite and baked and altered sedimentary rocks. The main crest of the mountains southward is formed of marble, hornstone, quartzite and garnet-epidote rocks, resulting from the intense alteration of impure limestone by the heat of igneous intrusions. These rocks are cut by large intrusions of quartz-porphyry and small diabase dikes. The entire range is flanked by foothills and *mesas* formed of well-bedded andesitic tuffs dipping away from the range at angles of from 10° to 30°, and representing the fragmental products of the old volcano, which once formed its cone.

The ores consist of chalcopyrite, together with copper glance, pyrite, zinc-blende, and a little galena. They occur in deposits which are, in part, beds of altered limestone tilted at steep angles and richly impregnated with metallic sulphides, and, in part, deposits formed in fractures along and across the quartz-porphyry and quartzite without any very definite relation to the igneous contact.

Near the Ronquillo smelter of the Greene Consolidated Copper Company the ore-bodies of the group of mines embracing the Capote, Veta Grande, Cobre Grande and Oversight properties occur mainly along these fractures. The outcrops are great ridges of iron gossan, traceable for long distances, and the ore-bodies are very large, one in the Capote being 165 feet by 125 feet, and oval in cross-section. These "veins" conform, however, in dip and strike, to the ore-bodies that consist of beds of altered limestone.

The ore-deposits continue for a distance of about 8 miles along the central portion of the range, and north of the Ronquillo group of mines, just mentioned, they pass into metamorphosed limestones impregnated with copper. In the exposures near the northern part of this area the ore is seen to be confined almost entirely to the garnet-epidote-diopside rocks, which occur interbedded with hornstones, marble, etc.; and, as will be shown later, this accords with the views of their genesis presented herein. In addition to the ore-bodies in course of exploitation, there are many beds that contain much galena and zinc-blende.

These copper-ores are usually very low in gold- and silver-content; but there are certain exceptions to this, notably the Alfreina mine, the ores of which carry high values in gold.

The development work at most of the northerly properties has not yet reached the sulphide ores. At the Puertecitos mine the working-tunnel passes through a bed 30 feet wide that carries a large amount of chalcopyrite, with a little zinc and galena, the ore averaging about 15 per cent. copper. This bed is capped by a white marble, which, as shown elsewhere, is a relatively impervious rock. The ore consists, approximately, of:*

	Per cent.
Chalcopyrite,	25
Galena,	5
Calcite,	35
Actinolite,	20
Quartz,	15

The chalcopyrite and galena show an evident association with the dull green, finely fibrous actinolite. The sulphides occur in grains up to three-fourths of an inch across; they are not crystalline, but of irregular form and of compound structure (*i.e.*, not of uniform crystalline orientation). The actinolite and calcite occur in patches, but the quartz is idiomorphic, and the crystals penetrate both the minerals just mentioned. The ore, however, appears to cover and enclose the quartz.

Germany.—Richard Beck has described very fully a deposit of this structural type in his recent book, and I therefore insert a translation of his description in full:†

"1. The ore-deposits of the contact area of the granite of Berggiesshübel, in Saxony.

"The ore-deposits of Berggiesshübel, in the so-called Elbe Valley mountains of southeastern Saxony, represent a specially well-studied and typical example of contact metamorphic ore-occurrences, and for this reason will be here first described, and in some detail, although they have long since lost their economic importance.

"At Berggiesshübel, in the moderately uptilted schist rocks, several granite stocks appear, among which the one of Markersbach occupies the foremost place by its size and by the extent of its contact phenomena. Close to its western border lies the mine district of the old mining town of Berggiesshübel.

"The outcrops of the various beds of the Phyllite formation and the lower Silurian formation are there distinctly seen terminating at the border of the

* These figures are based upon estimates made by measurement of specimens and thin sections of the ore.

† *Lehre von den Erzlagerstätten*, Leipzig, 1901, p. 609.

granite, and various exposures and other evidences prove that the surface of the eruptive stock dips at a low angle under the schists thus traversed. The sedimentary rocks thus adjoining and, in part, overlying the granite have been subjected to strong contact metamorphosis.

"Turning specially to the Silurian formation, we find that the clay slates were changed into hornstone, horn schists and knot-schist, while the diabase tuffs,—the so-called Schalsteine,—were changed into various kinds of hornblende schists, especially actinolite schist, also banded salite-hornblende schist. The limestone layers, however, intercalated in the clay schists and especially in the tuffs, were turned into marble beds, or, in part, into salite-garnet rock, or, finally, into magnetic iron beds.

"These limestone strata may be followed from NW. to SE. in their strike, for long distances, in many good exposures, deep limestone quarries and natural outcrops, from Maxen across the villages of Biensdorf and Gersdorf, to the point where they enter into the contact-area of the granite. Over this whole distance, however, these limestones are devoid of ore, except a few quite insignificant beds of red and brown hematite, which occur in quite limited patches, for example, at Nenntmannsdorf, at the boundary between limestones and schists.

"In the contact-area, however, the calcium carbonate has been partly or entirely displaced from these beds, and replaced by secretions from immigrant silicate and ore-solutions, such as salite and garnet, as well as magnetite and various sulphide ores. The distribution of the marble, calcium silicates and ores within the beds is very remarkable and diverse, and throws a bright light on the manner of this replacement metamorphosis.

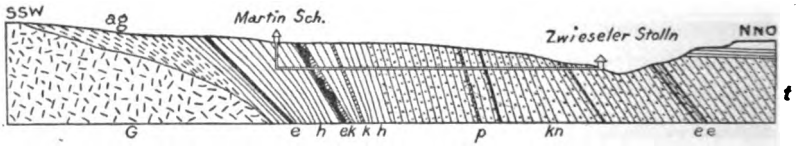
"First let us note that the marble still shows clearly the stratification of the originally dense Silurian limestone out of which it was formed. Even the alteration between thin limestone beds and diabase tuffs, which occurs not infrequently in the Silurian at that place, may repeatedly be observed in the contact-area between marble and hornblende schist, except that the limestone, wherever it formed thin streaks and layers, has for the most part been changed throughout into a light-green pyroxene rock.

"In the larger limestone layers in the contact-area one notices not infrequently a structure consisting of separate marble bands, separated by layers of salite-garnet rock, and also a thin-stratified alteration between garnet-rock and magnetic iron-ore. More usually, however, quite irregular nests and lumps of magnetic iron-ore lie in the midst of the marble, cutting across its stratification. In such cases they frequently penetrate into the marble with jagged or stringer-like projections. At some places, as, for example, in the limestone workings near the Hermann shaft, even irregularly vein-shaped masses of magnetic iron-ore were observed in the midst of the limestone. On the whole, the ore clings especially to the lower boundary of the marble bed, frequently swelling up from there, cutting with its upper boundary across the strata of the marble and entirely replacing it for long distances, in some places for a width of 5 m. Finally, the ore-bodies are at times traversed by ramified stringers of the garnet-rock, forming a network among themselves. It thus appears that the ore-mass was broken, but that the infiltration of the solutions furnishing the garnet continued after this mechanical disturbance. That phenomena of disruption took place during the contact metamorphosis, at the time of the transition of the dense limestone into marble, is furthermore indicated by the frequent stringers of coarsely foliated calcspar, which traverse the blackish marble as white bands. They seem to have been formed during the process itself, as primary stringers. Occasionally they carry some garnet.

"Other ores besides magnetic iron take part in the composition of the ore-beds of the locality, especially copper minerals, such as chalcopyrite, erubescite, copper glance, rarely gray copper-ore. From these have resulted a number of secondary copper-ores, malachite, etc. Less frequent admixtures are iron pyrites, arsenical pyrites, galena and zinc-blende.

"While the subsequent introduction of all these ores into the limestone beds of that locality is beyond question, doubts may still be entertained concerning the origin of the metalliferous solutions. Two theories may be advanced in regard to this point. One theory is, that the metallic compounds in question were originally finely distributed through the adjoining rock, especially in the diabase tuffs, and were only later concentrated through the contact metamorphosis, through redeposition in the limestone by means of mineralizing agents derived from the granite, after expulsion of the carbonic acid of the calcium carbonate. The other theory is that these metallic compounds were directly brought up with the granite from great depths, and were infiltrated into the adjoining rock in solution in the over-heated water accompanying the eruption. The latter theory has the greater probability, since all the hornblende schists and hornstones are rich in iron at the contact also,—much richer, in fact, than elsewhere, aside from the contact.

FIG. 1.



Section through the contact zone of Berggiesshübel, Saxony.

G = Markersbach granite; ag = andalusite-mica rock; h = hornblende and pyroxene-schists; kn = spotted schists; e = ore-bodies; k = crystalline limestone; p = quartz-porphyry; t = Sub-Turonian and Cenomanian.—R. Beck, *Erzlagerstätten*, p. 611.

"This is rendered still more probable by the fact that in the same district *ore-lodes* also exist in the granite, which are characterized by copper-ores, and, in part, traverse the ore-beds. They seem to represent the main channels of supply for the metallic solutions emanating from the granite.

"Finally, besides these copper-lodes, tin-bearing stringers are also known to occur in the metamorphic limestone-beds of that locality. These stringers consist of orthoclase, fluorspar, quartz and lithia-mica distributed in zones. Near them A. W. Stelzner also discovered tinstone; together with chalcopyrite and pyrite, as impregnations of certain strata of the beds, consisting mainly of chlorite.

"The Markersbach granite is thus seen to be surrounded by an aureole of highly diverse metallic compounds.

"The iron-mining industry of Berggiesshübel, formerly of some importance, is now practically extinct."

Gold-Deposits.

The recognition of telluride ores in contact-deposits is, I believe, new. It is expressly stated by Lindgren, as a result of his review of the literature on the subject and his own experi-

ence, that no tellurides occur in contact-deposits.* I have found several examples of this interesting type of deposit, which is clearly entitled to rank as a special class in metamorphic deposits. This at once brings up the question of permanence in depth of such deposits, discussed elsewhere in this paper.

Western Montana is a mountainous region in which there are several great areas of granitic rocks breaking up through sedimentary strata and earlier igneous rocks. Along the limestone contacts of these granitic intrusions (batholiths) ore-deposits are often encountered, though they are rarely of any great economic importance. Most commonly they are of the Kristiania type, examples of which may be found at Georgetown, Cable, and other localities west of Anaconda; in the Highland Range south of Butte; in the Indian Queen mine, on Birch Creek, in Beaverhead county; at Elkhorn, and at very many localities about the granitic borders mentioned. There are, however, examples of contact metamorphic deposits of the Cananea type at Elkhorn and Philipsburg.

Bannack Type.—The placers of Grasshopper Creek, at Bannack, were the first great gold-placers discovered in Montana. Attention was soon attracted by the ledges on the slopes above the basin, in which the richest gravels occurred, and a "lode" excitement, almost as fierce as that of the placer-days, followed. Enormously rich ores were taken out, several mills were erected, and the ground was burrowed to a shallow depth wherever the pockets and streaks of rich ore occurred. Yet, despite the attractive prospects and good returns, the ore-deposits have never been explored in depth, the deepest shaft being about 300 feet deep.

The ore-deposits are typical contact metamorphic deposits. A central boss of diorite, about three-fourths of a mile in diameter, is surrounded by a series of upturned Paleozoic limestones and associated shaly rocks, dipping away from the granite on all sides at angles of 10° to 45°. This dome or anticline has been eroded, and the granite now forms the surface of the low central portion of a basin, whose surrounding heights are formed of limestones flanked by heavily-bedded

* "Character and Genesis of Certain Contact-Deposits," *Genesis of Ore-Deposits*, p. 717, under heading "Constituent Minerals;" also, *Trans.*, xxxi., 227.

quartzites of Carboniferous age. The diorite intrusion, though laccolithic in its general character, has a very uneven contact, breaking irregularly through the limestones, and holding included blocks of the latter within its mass, while tongues of the igneous rock project out and penetrate the adjacent sedimentary rock.

The limestones are highly altered about the contact; but, owing to the fact that the diorite comes in contact with limestones of varying composition, the resulting rocks differ greatly in mineral constituents. In the main, these contact rocks are either impure marbles or are composed of brown garnet, epidote, calcite, and other common contact metamorphic minerals. The ore-deposits, in part, follow the actual contact between diorite and contact rocks. Where limestones prevailed, the ore-bodies were irregular; tongues and chambers of ore extend out into the limestone, and the ore (now oxidized) consists of porous iron-stained quartz the cavities of which show the crystalline form and striations of coarsely crystalline gold-bearing pyrite. Where the garnet rocks prevail the ores do not follow the contact, except in a general way, but occur in the more garnetiferous bands which alternate with epidotic rocks and marbles and mark the alteration of beds of limestone of differing composition. The ore-minerals consist of telluride of gold, together with some free gold, disseminated and rather abundant specular iron, some pyrite and less chalcopyrite. As usual, the telluride ores are spotty, occurring in rich bunches, but there is also a general dissemination through the rock, and all the garnet-specular-iron rock contains a few dollars per ton in gold, as shown by a large number of assays.

Elkhorn.—The Elkhorn district is situated in central Montana, about half-way between Helena and Butte. The ore-deposits occur at the eastern border of the great granite area that covers the greater part of Jefferson county. At Elkhorn this granite cuts abruptly across the ends of tilted sedimentary beds embracing a great variety of rock types of different geologic ages. The granite is of Tertiary age, and later than the fragmental andesitic rocks which form the neighboring peaks and which rest upon the sediments. The principal ore-deposit, that of the Elkhorn mine, is not a contact metamorphic deposit, but a "saddle" deposit formed in

the axis of a steeply dipping fold, between an altered shale (hornstone) hanging-wall and a crystalline dolomite crushed along the fold. The sedimentary rocks near the igneous contacts are highly altered, and are good examples of contact metamorphic rocks. Iron ore-deposits on Elkhorn Peak are contact-deposits of the Kristiania type, and there are several true contact-deposits of pyrite of too low-grade to work.

A half mile northwest of the Elkhorn mine, on the western slope of a steep and wooded ridge composed of altered sedimentary rocks, lies the Dolcoath mine, a property as yet in the prospect stage. Shipments of sorted ore have been made, and the oxidized ore shows native gold flecking the rock. The ore is a bed of garnet-diopside rock (altered limestone) 15 to 18 inches thick, dipping at 55° to the east and carrying gold in bismuth sulphide (bismuthinite) and bismuth telluride (tetradymite). This ore stratum is conformable with the adjacent beds, but differs from them in composition. The rocks have been studied by Dr Barrell,* who determines their approximate composition to be as follows:

Ore Stratum.		Footwall.		Hanging-Wall.	
Diopside	45	Diopside	30	Augite	5
Garnet	40	Garnet	10	Biotite	25
Calcite	12	Basic feldspar	60	Basic feldspar	66
Sulphides, with gold	3			Sulphides, no gold	4
	100		100		100

Samples from the sacked ore of the upper levels yielded $156.00 per ton in gold, but average samples from the bottom level, made during an expert examination of the property by a Butte mining engineer, yielded but $4.50 per ton in gold.

Similkameen Type (British Columbia).—The Nickel Plate mine, which promises to be a great gold-producer, is situated near the Similkameen river, Osoyoos mining division, west of Penticton.† The ore consists of a garnet-calcite-epidote rock, whose mineralogical composition and geological occurrence both show that it is an altered impure limestone. The ore-mineral is arsenical pyrites, disseminated through this gangue

* *Op. cit., Am. Jour. Sci.*, April, 1902, p. 295.

† *Report of the Minister of Mines of B. C.* for 1900, p. 883.

rock and concentrated in the high-grade ores, which occur in extraordinarily rich bands. Mr. H. V. Winchell informs me that the ore-body is of contact metamorphic type. The specimens which he collected show the arsenopyrite to be confined, almost exclusively, to the garnetiferous portion of the ore, the green (epidotic?) portion being very low-grade.

So far as known, arsenopyrite has never before been found in contact-deposits. It has, however, been observed in certain pegmatitic veins which are believed by some observers to be of pneumatolytic origin.*

Changes in Rocks due to Contact Metamorphism.

General Effect.

It is a well-known fact that certain intruded igneous rocks have exercised a profound influence upon the wall-rocks confining and adjoining them, while other types of igneous magmas have produced only a slight effect. To a large degree this alteration, or contact metamorphism, is due, as has been shown by Iddings,† to the length of time the adjacent rocks have been heated. If the conduit of a volcano is broken through sedimentary rocks, and this conduit serves as a vent for a prolonged period of time, and is finally filled by magma that cools as a coarse-grained rock, it is evident that these conditions favor extreme metamorphism of the adjacent material. If a small sheet or dike breaks through sedimentary strata, and is promptly chilled, the magma exercises but little apparent influence upon the wall-rock. It is, therefore, largely a question of physics. The great intrusion takes a long time to cool; the magma crystallizes as a granular rock, and the adjacent rocks are heated for a long period. It is partly, therefore, a question of the mass of the magma cooling. Professor Kemp‡ has succinctly stated the known facts upon this subject in his recent paper upon the "Rôle of Igneous Rocks." On the other hand, although the result of such long-continued heating of

* O. A. Derby, "Notes on Brazilian Gold-Ores," *Trans.*, xxxiii., 282.

† "Electric Peak and Sepulchre Mountain," 12th *Ann. Rept. U. S. Geol. Survey*, Pt. I., pp. 569–664.

‡ *Genesis of Ore-Deposits*, p. 692; also, *Trans.*, xxxi., 180.

wall-rocks has been recognized by geologists for many years, the fact that different rocks show varying effects has been commonly imputed to the nature of the rock, and until recently there has been no lucid discussion of the effect of contact metamorphism upon sedimentary rocks. Quite recently there appeared a paper by Prof. Joseph Barrell, entitled "The Physical Effects of Contact Metamorphism."* In this paper it was shown that the metamorphism of sedimentary rocks by the heat of igneous masses is accompanied by the liberation of enormous volumes of gases, with attendant shrinkage of volume and the formation of vein-fissures and impregnation deposits. Several writers, particularly Vogt, Kemp, and Lindgren, have recently drawn attention to the metasomatic and impregnation effects of the mineralizing vapors coming from the cooling igneous magma and carrying dissolved metallic minerals along favorable channels in the contact zone. In addition to this eruptive after-action of Vogt, there is a more or less complete expulsion of carbon dioxide and combined water from the sedimentary rocks, accompanied by the formation of new minerals and the induration of the rocks. As is well known, the alteration of pure sedimentary rocks by contact metamorphism is as follows: Sandstone to quartzite; clay-stone, or shale, to hornstone; limestone to marble; but as, in nature, these pure rocks seldom exist, and it is the impure limestones, sandstones and shales which are most common, the alteration of such rocks produces a more or less striking metamorphism—the material recrystallizing as garnet, wollastonite, epidote, etc.

Changes in Mass, Volume, and Mineral Composition.

As the chemical elements remain the same in the altered as in the unaltered rocks, save for the greater or less expulsion of water and carbon dioxide, it is possible to tabulate the mineralogic changes. This has been done by Professor Barrell, and from his table it is possible to work out not only the original composition of the unaltered sediment, but the changes in mass and volume which have taken place in the process of metamorphism.

The greatest changes in volume are due to escaping gases

* *Am. Jour. Sci.*, vol. xiii., April, 1902, p. 279.

and vapors. His conclusion that metasomatic additions during this metamorphism are prevented by the internal pressure of the escaping gases is not regarded as correct for all cases, though it is based upon the belief that by the time the pressure is relieved sufficiently to permit the ingress of heated waters or mineralizing vapors from the adjacent magma the rock is recrystallized; also, as a result of the hydrostatic pressure of the still liquid magma, it is usually dense. While it may be true, as stated by Barrell, that metasomatic infiltration of the metamorphic strata does not *usually* take place, yet instances have come within the observation of the writer where such action is very pronounced. Differential shrinkage has given the strata the porosity of a burned brick, and, as aptly noted by Barrell, the analogy is the more appropriate since in these cases the action is one of thermal metamorphism, without sufficient pressure to result in a close texture. Two instances are given by Barrell, both in the Elkhorn region of Montana, one already quoted. The conditions in the region are particularly favorable for a study of the varying effects of the thermal metamorphism caused by the intrusion of a large igneous mass into sediments of widely varying composition. The granite mass cuts across tilted strata whose inclination favors alteration, and whose wide variety of composition results in striking differences in the porosity of the altered rock. Inasmuch as the altered sediments are on top of the granite, they have not been subjected to the same pressure that would have changed them if they had been part of the rock enclosing the intrusion. Moreover, the pressure would be transmitted by the denser layers, and would not be transverse to the borders.

A consideration of the physical conditions involved shows that in many instances the porosity induced by thermal metamorphism of rocks forming the side-walls of igneous intrusions is probably counteracted by the hydrostatic pressure of the magmas. It has been found that metamorphism of the sedimentary rocks would be practically completed before solidification of the magma begins,* and completed while the magma was able to act hydrostatically and transmit lateral pressure.

* Barrell, *op. cit.*, p. 294.

Under these conditions the shrinkage of the vertical walls would be largely lateral, and result in a corresponding lateral expansion and a *vertical subsidence* of the magma. Where, however, as is so commonly the case, great masses of granite are capped by relatively thin layers of altered sediments, as, for example, in the region about Helena, Montana, the sediments above the magma, though subjected to pressure, would transmit this pressure along the heavier and more competent beds; while the intervening, weaker members would retain the porosity due to recrystallization and escape of gases, except, of course, at the immediate contact with the magma. It is evident that in such cases the porosity of the strata near the igneous inclusion favors the escape of pneumatolytic gases along and through the porous strata.

Genesis of Contact Metamorphic Deposits.

Cause of Contact Metamorphism.

That contact metamorphism is due to intrusive masses of molten magma is now generally accepted. The usual theory advanced is that the heat of the magma, together with the watery vapors given off by it, have caused the metamorphism. This is the explanation advanced by both Lindgren and Vogt. The latter has quoted the Swedish physicist, Arrhenius, as showing that the physical and chemical action of watery vapors upon a magma proves such vapors to be competent to extract the heavy metals from the magma. Barrell, however, has shown that the intrusion of magma heats the adjacent sedimentary rocks to very high temperatures, generating enormous volumes of gas and watery vapor by changes caused in the nature of the sedimentary rocks, and, moreover, that the process of recrystallization is complete before the magma cools. This latter conclusion, reached from a study of the physico-chemical actions involved, is confirmed by the field-evidence at Elkhorn, Mont., where tongues and dikes of the igneous rock penetrate the contact rocks, and accounts for similar dikes which at Boundary Creek, B. C., cut the *contact ore-bodies*. It is, therefore, not necessary to assume that watery vapor from the *cooling igneous mass* has played the only part in the metamorphism.

Whether we do or do not accept this statement as completely

proven, it must be admitted that the effect of the igneous magma upon its confining walls is not limited to this first metamorphism of the sedimentary rock. The molten magma gives off vapors,—pneumatolytic vapors they have been called,—and that these escape into the adjacent rocks we have abundant evidence. As some geologists appear to question our knowledge concerning this action, it may be well to summarize the known facts concerning the gaseous emanations of igneous rocks. At present our knowledge of these is derived from (1) analyses of the gaseous emanations of volcanoes and lava-flows; (2) analyses of the gases occluded in cold rocks; (3) analyses of the sublimation-products formed by fumaroles; and (4) evidence of contact metamorphism of included masses of sediments entirely surrounded by the igneous rock.

Concerning the first of these proofs, there is considerable direct positive evidence furnished by competent observers and chemists. This has been summarized by Geikie,* who states that hydrochloric acid is evolved in abundance from the clefts at Vesuvius; also vast quantities of free hydrogen or combustible compounds of this gas are given off from Vesuvius, and were distinctly recognized by Fouqué in the eruptions of Santorin.† These gases, when studied spectroscopically, were found to contain traces of chlorine, soda and copper. Analyses, by Fouqué, of the gaseous emanations were found to contain abundant free oxygen, as well as hydrogen, and one analysis gave the results in column I.:

	I.	II.
Carbon dioxide,	0.22	15.38
Oxygen,	21.11	13.67
Nitrogen,	21.90	54.94
Hydrogen,	56.70	8.12
Marsh gas (methane),	.07	5.46
Argon,	.....	0.71

In column II. is given the analysis by Moissan of the gas collected by Lacroix from a fumarole on the Rivière Blanche, Martinique, whose temperature was high enough to melt lead rapidly, but not zinc (*i.e.*, about 400° C.). An abundance of sulphur and ammonium chloride was deposited about it.‡

Fouqué infers§ that the water vapor of volcanic vents may

* *Manual of Geology*, p. 188.
† *Santorin et ses Eruptions*, p. 225.
‡ *Comptes Rendus*, CXXXV. 1085, 1902.
§ *Santorin et ses Eruptions*, p. 225.

exist in a state of disassociation from the molten magma when lavas rise. Fluorine and iodine have likewise been observed.

In a recent lecture, Prof. Eduard Suess* has directed attention to the gaseous emanations of volcanoes, and indicated their part in the formation of mineral veins. After describing his own observations at Vesuvius, he says:

"Turning now to the gases accompanying the eruptions. After steam, chlorine and gases containing sulphur are the most important, and carbonic acid gas comes next. Their occurrence follows a definite law. So far as it has been possible to approach them, all fumaroles actually within vents contain steam; but the hottest fumaroles (over 500° C.) on the surface of cooling lava-streams, where approach is easier, are dry. In the emanations from these high-temperature fumaroles are found chlorine compounds, and along with them fluorine, boron and phosphorus,—substances which are the first to disappear as the temperature of the fumarole sinks. Sulphur persists longer, often combined with arsenic. Carbonic acid is given off freely till a much later stage, sometimes till the fumarole is comparatively cool, notwithstanding that it is observed in the hottest dry fumaroles. Fumaroles in different 'phases of emanation' may occur quite near one another. The steam of the volcano cannot be derived from vadous infiltration; for, if it is, whence the carbonic acid? Both must come from the deeper regions of the earth; they are the outward sign of the process of giving off gases which began when the earth first solidified, and which to-day, although restricted to certain points and lines, has not yet come to a final end. It is in this manner that the oceans and the whole vadous hydrosphere have been separated from the solid crust. Volcanoes are not fed by infiltration of the sea, but the waters of the sea are increased by every eruption."

Concerning the analyses of the gases occluded in the cold rocks, the evidence is not so satisfactory. From the study of microscopic slides it is well known that gaseous and watery inclusions occur in crystalline rocks, and various attempts have been made by chemists to estimate the quantity of included vapor so held. Recently, Dr. M. W. Travers, in a paper on the "Origin of Gases Evolved on Heating Mineral Substances, Meteorites, etc.," has shown "that in the majority of cases

* *Geographical Journal*, London, vol. xx., p. 520, November, 1902.

where a mineral substance evolves gas under the influence of heat, the gas is the product of the decomposition or interaction of its non-gaseous constituents at the moment of the experiment."*

Notwithstanding this fact, however, we have abundant evidence, in the analyses of obsidian and pitchstone, of the presence of a considerable proportion of water; and it is well known that these rocks change into pumice on heating. Also the presence of fluorite in the dense and almost glassy phonolites of Montana is to be remarked here. The Hawaiian Island lavas, though highly vesicular, contain practically no water, and Whitman Cross† has noted the absence of steam from the lava cauldron of Kilauea, although there was an abundance of sulphurous vapors and brown vapors of an unknown composition given off from clefts immediately adjacent to the lava lake.

Attention might also be directed to the recent work of Armand Gautier,‡ in which he shows that granite and other crystalline rocks evolve large quantities of vapors when heated.

Third, the analyses of the sublimation products found about fumaroles show conclusively that metallic salts, as well as non-metallic, are given off by the igneous emanations, or result from reactions between the escaping vapors and the solids with which they come in contact. Besides sulphur, chlorides of sodium, potassium, iron, copper and lead also occur, and specular iron, oxide of copper and iron chloride have been observed by Geikie and Fouqué.§

Fourth, the evidence of contact metamorphism, as studied in included masses, affords direct proof of the action of pneumatolytic vapors when the original composition of the included mass can be known with any certainty. Under such conditions one can exclude the reactions indicated in the case of the confining walls of the magma, and there is no doubt that in many cases there is a direct migration of material, particularly silicates, also fluorine and chlorine, together with copper sulphide and iron oxide, into the included masses. Such masses have been studied by Lindgren‖ at the Seven Devils district of

* *Proc. Royal Soc.*, vol. lxiv., p. 142. (Read Nov. 24, 1898.)

† Verbal communication.

‡ *Zeit. Prak. Geol.*, vol. ix., p. 383, 1901.

§ Geikie, *Manual of Geology*, p. 188.

‖ "Character and Genesis of Certain Contact-Deposits," *Genesis of Ore-Deposits*, p. 722; also, *Trans.*, xxxi., 232.

Idaho, and by Kemp in the San José district, and Tamaulipas, Mexico.

Inasmuch as included fragments of pure limestone are changed to garnet-rock and impregnated with metallic sulphides, vesuvianite, axinite, etc., whose constituents are not normal to any of the original rocks surrounding the intrusion, the evidence is satisfactory that there was a migration of material in the form of vapor from the igneous magma into the adjacent rocks.

From this evidence we are justified in assuming that there is a series of "eruptive after-effects," as Vogt has called them, which start at the moment of the intrusion and continue until the rocks have completely cooled, and which grade one into the other.

On the other hand, if the resulting metamorphic rocks are porous, as in certain cases we know them to be, the vapors from the cooling magma will be "blown in" (to use Vogt's term), and ore-deposits may be formed in this way.

Professor Suess, in the lecture already quoted, has called renewed attention to the fact that mineral veins are to be regarded as the result of waning phases of volcanic (igneous) phenomena. "Hot springs may be taken as the latest phase of a whole series which led up to the present deposits of ore." His whole paper is an argument against the theory that either the majority of ore-deposits or of hot springs are of meteoric derivation.

That gaseous emanations rising through fissures toward the earth's surface can mingle with ordinary meteoric ground-water must be admitted, and it is believed that much of the discussion between those who advocate the deposition of ores by circulating ground-waters, deriving their metallic contents from the generally cold rocks traversed in their course from the earth's surface downward and back again to the surface, has arisen because of the failure to recognize that in this mingling of igneous emanations and ground-waters we have the true explanation. The ground-waters alone, either cold or heated, would not ordinarily take up enough material from the rocks traversed by them to enable the waters to deposit ores in veins. On the contrary, it is the gaseous emanations carried by the ground-waters into trunk-channels that deposit ores by reaction with other currents, wall-rock, etc.

Contact metamorphic deposits, properly so-called, occur as a result of the metamorphism of sedimentary rocks by igneous intrusions. The definition thus excludes all deposits formed along ordinary contacts, due solely to circulating waters, even where such waters contain substances derived from igneous emanations dissolved in the waters,—as, for example, the Mercur, Utah, and Judith Mountain, Montana, deposits, and other ore-bodies of similar character. When the ore-minerals are intergrown with the garnet-epidote and other gangue minerals, the deposits are clearly pneumatolytic.* Another class is the result of later impregnation by igneous emanations penetrating a porous stratum, the stratum itself made porous as a result of metamorphism. A third class are the result of the precipitation of copper or other sulphides from ascending alkaline solutions, supposedly hot waters, by the lean sulphides formed by pneumatolytic action (deposits of the second class). In the first class the ores are of simultaneous origin with the gangue minerals which are admittedly due to contact metamorphism. In the second class, ores were introduced subsequent to the metamorphism of the rock (Elkhorn type). The third is probably difficult to distinguish from the first, but is believed to exist at Cananea, Mexico, though not the kind designated by that name.

Barrell has calculated the changes taking place in two examples at Elkhorn. The first is a thin band of hornstone occurring in marble and consisting of 50 per cent. of diopside, with 46 per cent. of feldspar and 2 per cent. each of quartz and fluorite. It is evident that the crystallization of diopside and feldspar left the stratum very porous, and that the pores were filled by quartz and fluorite from pneumatolytic vapors.

The second instance given by him is the ore-stratum of the Dolcoath mine, already described. This is a typical instance of a porous layer.

"It is seen that even if all the calcite of the ore-bearing stratum be regarded as a primary mineral, the shrinkage in the ore-stratum has been somewhat greater than in either the foot- or hanging-wall, since the feldspars and biotite are minerals which, as shown by the alkalies present, were formed from sediments not fully hydrated or carbonated. Moreover, a microscopic examination of the ore-stratum shows parallel sinuous cracks due to tension, and not to shear, and now filled with calcite. Elsewhere in the section the calcite exists as a sponge, holding garnet, diopside, and ore-grains within it, and its secondary nature is not so

* *I.e.*, formed by the action of gases or vapors at high temperatures and pressures reacting upon solid materials.

clear. The ore is associated with the calcite, and also with a certain coarser crystallization of the diopside."*

Professor Barrell calculates the shrinkage of the ore-stratum at 40 per cent., of the hanging-wall at 15 per cent., and the footwall at 25 per cent., so that it is evident that we have here a steeply inclined pervious stratum capped by a relatively dense impervious bed, and offering a favorable channel for uprising vapors, given off by the cooling magma beneath, or for circulating waters.

The source of the metallic mineral deposited in these contact-rocks, if not positively known, is commonly assigned to the solfataric vapor given off by the cooling igneous magmas. There has always been more or less skepticism concerning the source of the oxide of iron, magnetite and specularite, which are such common and characteristic features of true contact-deposits. Inasmuch as the disassociation of the interstitial water of the sedimentary rocks by the intrusion of highly-heated magma would provide a sufficient supply of oxygen, the occurrence of such ores, produced by reaction with the iron-compounds present, would be explained, while the fact that such deposits are almost entirely confined to the immediate vicinity of the igneous contact can be readily understood.

Permanence in Depth of Ore-Deposits of this Class.

So far as development and experience show, the deposits of the Kristiania type occurring at actual contacts are very bunchy, and cease in depth; a notable example being the Seven Devils, Idaho, deposits. In the Cananea, Mexico, example, and the Boundary, British Columbia, deposits, the copper-ore is more uniformly distributed, and there seems no theoretical reason why the primary sulphide-ore should not continue of unchanged tenor in depth down to the igneous contact. In the case of the gold-ores, both tellurides and arsenopyrite, so little is known that no prognosis can be made. The deepest workings at Bannack are but 300 feet below the surface. At Cripple Creek, where the deposits are not of contact-metamorphic origin, though they are considered to result from volcanic emanations, the values decreased with depth. However, recent discoveries indicate workable bodies of auriferous gray copper at greater depths. The Cornwall tin- and copper-veins are

* *Op. cit.*, pp. 295, 296.

now practically worked out. At the Dolcoath the ore is low-grade at 150 feet. If the theory of genesis be true, there is no reason now known for the impoverishment of contact metamorphic deposits in depth.

Mineral Veins near Igneous Contacts.

In addition to the pneumatolytic deposits on igneous contacts and those in altered strata near the contacts, there are many productive mines working true veins cutting the igneous rock and the contact-rocks above them. Such vein-fissures are caused both by the contraction due to the crystallization and cooling of the igneous rock and by the shrinkage of the metamorphic zone above the igneous rock. Examples of this type have already been mentioned. As shown by Pirsson,* the radial fissures which form so remarkable a feature of certain igneous centers are not due to the initial expanding force of the intruded magma, but to the contraction-cracks. The vast amount of heat given off by the cooling magma effects a considerable expansion of the surrounding rocks. As the magma and its surrounding shell of heated sediments cools down it must contract, and this contraction will result in a cracking both of the igneous rock and the contact-zone; and, if the rocks of the contact-zone are homogeneous, the cracks will assume a more or less radial position. If these cracks extend to a depth sufficient to reach still molten magma, they will be filled, and dikes will be formed; if not, the cracks become channels for pneumatolytic vapors and later circulating waters, and thus pegmatite veins and true mineral veins may be formed, and may merge into one another. It is possible that the (now brecciated) Granite Mountain vein at Philipsburg, and the very productive veins at Marysville, Montana, may have originated in this manner. But, in addition to radial cracks, the shrinkage would also tend to produce cracks parallel to the borders of the intrusion,†—a phenomenon observed in casting, and also in the cooling of lava-sheets,—as, for example, those of Obsidian Cliff, in the Yellowstone Park region, a discussion of which has been given by Iddings.‡ As circulating solutions travers-

* "Complementary Rocks and Radial Dikes," *Amer. Jour. Sci.*, vol. l., 1895, p. 116.

† For ore-deposits of this type, see Beck, *op. cit.*, p. 182, Fig. 119.

‡ *7th Ann. Rept., U. S. Geol. Surv.*, for 1885-6, pp. 249–295.

ing contact-zones would course through the more basic differentiated part of the magma, which is well known to be richer in metals than the normal magma, there has been a combination of conditions favoring ore-formation, and it is easy to see why such ore-deposits occur in or near the contacts of great igneous masses.

I hold that the metallic contents of such veins are not gathered by ordinary meteoric water, as maintained by Van Hise. The water-content of the sedimentary rocks (ground-water) present at the time of eruption was expelled by contact metamorphism. The ore-forming solutions were in part of direct igneous origin;* these primitive hot vapors and waters rise and penetrate the zone of circulating meteoric waters, heating the latter and charging them with both metallic salts and with fluorine, chlorine, boron and other active mineralizers. The resulting mixture of plutonic and meteoric waters is a much more energetic solvent than normal ground-water, and is capable of adding metallic salts extracted from the rocks traversed by the waters to the original material derived from the igneous emanations.

Conclusions.

Contact metamorphic ore-deposits occur about the margin of intrusive masses of granular igneous rock, either at the actual contact or in the zone of metamorphosed sedimentaries. The deposits of economic value occur only where strata or blocks of impure limestone have been crystallized as garnetiferous or actinolite-calcite rocks, with consequent porosity. The ore-minerals are intimately associated with these aluminous silicates, and may be either intergrown, or metasomatic replacements, or the result of interstitial filling with partial replacement. The conversion to garnet-epidote-calcite, etc., rock was complete before the consolidation of the igneous rock. The ore-minerals were introduced in gases and vapors—solfataric emanations—from the eruptive masses of which they constitute pneumatolytic after-actions, or by hot circulating primitive waters given off by the cooling igneous mass. This theory of the genesis being true, the deposits should extend downward in depth to the granular rock.

* *I.e.*, primitive or igneogenous. The geyser waters of Iceland, New Zealand and the Yellowstone regions are probably mainly of this character, as maintained by Suess.

Discussion.

(*Trans.*, xxxiii., 1070.)

W. L. Austin, New York, N. Y.:—In Mr. Weed's interesting paper, frequent reference is made to the Cananea copper-deposits, which are said to have been so vigorously exploited that they produced 14,000,000 lb. of copper in 1901.

The ore-bodies which yielded this large quantity of metal are described as a product of contact-metamorphism, and in Mr. Weed's genetic classification of such deposits, they receive a place under the sub-heading, "Deposits impregnating and replacing beds of contact-zone." They are considered by Mr. Weed to represent a special type under this head, and are further classified as: "1. Chalcopyrite deposits: (*a*) Pyrrhotite ores; (*b*) Magnetite ores, Cananea type."

In condensing much information into a comparatively small space, the presentation of a subject may be so abbreviated as to detract from its clearness. The situation at La Cananea, considering its importance from an economic as well as scientific standpoint, may be worthy of more detailed description. As Mr. Weed rightly remarks, "structural differences are so important, and have so marked a bearing, not alone on the theory of their genesis, but, also, in the working of the deposits and a determination of their value as mines, that they merit a full discussion."

It is my present purpose: (1) to show that it is doubtful whether the copper of La Cananea is mined, except to a limited extent, from contact-metamorphic deposits; (2) to emphasize the importance of the mineral-bearing porphyry in connection with the genesis of the Cananea deposits; and (3) to question the correctness of Mr. Weed's opinion that, in this locality, "the deposits should extend downward in depth to the granular rock."

Contact-metamorphic ore-deposits are very common in the West and Southwest. Among the better known of those in which copper is the principal economic mineral are those of the Seven Devils district, Idaho; Saline Valley, California; the Planet mine on Bill Williams Fork, Marble mountain, in the Santa Catalina mountains, and Clifton, Arizona; La Cananea, and the Santo Niño deposits on the Yaqui river, Sonora; Terasas Station, Chihuahua; and La Jibosa mine, Velardeña copper-

mine, and Sacrificio mountain, Durango. There are many others which I have not personally visited, but concerning which I have received private communications, or have found described in current technical literature.

These may all be classed together as ore-deposits occurring at or near the contact of igneous rocks with limestone beds, and owing their existence to the presence of the eruptives.

This general type of deposit is recognizable at first sight; but it is not always with a simple contact that the observer has to deal. Associated with the actual contact ore-bodies are mineralized eruptives, fissure-veins and replacements in the limestone. Mr. Weed, recognizing the variations displayed by deposits of this description, has proposed a tentative classification, which might be further discussed to advantage.

By reason of the very nature of the genesis of these deposits, there must be much diversity among them. In fact, hardly any two of them are exactly alike. They all have a certain mutual resemblance, and differ radically from any other class; but, unless a broad significance is given to the term contact-metamorphism, it will scarcely cover them all, and, in any event, there will be almost as many "types" as deposits.

The selection of the Cananea deposits as typical of contact-metamorphism, and the ascription to this type of the large production of copper quoted above, seems to me to be ill-advised; and the statement that in this instance the primary sulphide-ore should continue of unchanged tenor in depth down to a hypothetical contact with granular rock, certainly calls for further elucidation.

There are numerous contacts between the limestone and the igneous rocks of the Cananea district;—in fact, all the limestone patches are almost surrounded by porphyritic rocks of one kind or another;—but neither at any one of the important mines, nor at any other points so far as I know, has a contact between the limestone and a granular igneous rock been observed.

The ore-deposits of *La Sierra de la Cananea*, as hitherto developed, are scattered through the mountains along a N.W.–S.E. belt for about 8 miles. Puertocito is at the extreme northern end of the belt; the Elisa mine at about the middle; Capote

basin (with the Capote, Oversight, Veta Grande and Chivatera mines) are south of the Elisa; and at the southern end is the Cobre Grande mine. The Elenita deposits are really a part or Puertocito. At various points between these main ore-bodies are smaller ones.

At Puertocito and Elenita there are masses of garnetiferous minerals with associated copper carbonates and silicates, pyrite, chalcopyrite and bornite; at the Elisa there are irregular bodies of chalcopyrite along a fault-fissure in the metamorphosed limestone; at the Oversight and Capote mines there are much larger masses of feldspathic porphyry carrying chalcocite, which have yielded much the greater part of the copper produced in the district. The deposits of Elenita and Puertocito had no part in the large copper-production mentioned in Mr. Weed's paper; not until late in April, 1903, was any ore shipped from this part of the belt.

At the present time (April, 1903) the Oversight mine occupies the place of honor among the developed properties, having temporarily exceeded the production of the Capote, which was the first large *bonanza* found in the district. The first-class ore of the Oversight is a soft, white feldspathic porphyry, heavily mineralized with chalcocite. At the southern end of the mine, the surface-indications of underlying ore-bodies are so slight that one not very familiar with the characteristics of deposits of this class would hardly have ventured to predict the discoveries which have been made a few feet below. The porphyry shows at the top no mineralization; no gossan; no "copper stains." The solutions which effected the decomposition of the original pyrite, carried the iron with them and deposited it elsewhere,—a process which can be seen in operation to-day in other parts of the district. In such cases, silica and silicates are usually substituted for the minerals removed.

Underneath there is an ore-body of irregular shape, already developed for several hundred feet in depth, and in places several hundred feet wide. It is in reality a southerly continuation of the Capote ore-zone—a second great concentration of chalcocite in the porphyry. Its limits as here stated are merely those of the ore rich enough to be shipped; in fact, the chalcocite-bearing rock merges into cupriferous pyrite bodies of very much larger dimensions, but of lower grade. This much is

known: but what is the extent of these ore-bodies, or how many more of them there may be, has not yet been ascertained. Only the first-class, and the higher grades of the second-class ore, are at present taken out; lower-grade material is left standing.

It is not my present intention to discuss the extent and value of the Cananea ore-bodies. That matter has been briefly touched upon, only in order to bring out the fact, that by far the greater part of the copper produced by the mines of La Cananea has come from masses of mineralized porphyry, and not from "chalcopyrite ore-bodies carrying accessory galena, ... practically confined to the rocks resulting from the alteration of impure limestones." A statement of this kind, coming from such an authority as Mr. Weed, might possibly cause others to feel warranted in making large expenditures upon deposits of the class indicated, basing their hopes on the supposition that the *bonanzas* of La Cananea were found in contact-metamorphic deposits, with a probability of their extending "downward in depth to the granular rock."

Porphyry is by far the predominating rock along the Cananea ore-belt. I use the term "porphyry" in its general sense, for there are several varieties. Possibly all varieties have had their origin in the same eruptive magma, the sub-species being due to magmatic differentiation, or to the incorporation of portions of other rocks with which the eruptives came into contact. In places is found typical quartz-porphyry; but where the ore-bodies occur, the quartz is not so much in evidence. There are in the district other varieties of igneous rocks, such as granite, diorite, diabase and andesite; but these are mostly at some distance from the ore-belt, and as far as I know are not mineralized to any noticeable degree. The porphyry, however, wherever it has been artificially exposed within the entire length of 8 miles here in question, is more or less pyritic, and in places the sulphides are massed so as to form ore-bodies. The mineral belt has been extensively prospected, and tunnels many hundreds of feet in length cross its trend in a number of places. In these tunnels, many of which are considerable distances away from the producing mines, this mineralized porphyry is exposed; and at such points its character can be studied to advantage. It extends from the mines on the extreme north to those on the extreme south, and is essentially

the mineral-bearer of the district. The limestone occurs only in spots. Where the heavily mineralized porphyry has come into contact with this limestone, there are the usual contact-metamorphic phenomena; but these ore-bodies are of subordinate commercial importance; in fact, but for the mineralized porphyry the history of La Cananea would have been a totally different one.

The quartzites do not contain mineral deposits, except where cupriferous solutions from the decomposing porphyry have found cracks and fissures in which to deposit their burdens; and these are practically a negligible quantity.

Where the limestone has been metamorphosed by contact with the porphyries, it has become one of the most, if not the most, resistant of the rocks of the district. Proof of this statement is furnished by the garnetiferous bluffs which constitute such prominent landmarks at the Puertocito end of the belt. Not in this district only, but everywhere, such resistance to weathering is characteristic of rocks thus metamorphosed; for the process itself is largely one of silicification.

The ore-bodies which have made La Cananea famous are soft porphyritic masses, partly of mineralized porphyry, partly of dark-colored plastic clay less heavily charged with copper-ore. The one merges insensibly into the other, and much of the material is of a nondescript character, depending on the degree of decomposition which the rock has undergone. It bears no resemblance to metamorphosed limestone, although fragments of that rock are found in it, as are also masses of quartzite.

It is common, where porphyritic flows have broken through limestone beds, to find included masses of the latter caught in, and surrounded by, the porphyry; and the Cananea deposits are no exception.

The ore is so soft that no amount of timbering can hold the workings open; the stopes have to be filled as soon as the ore is removed. The ground swells to such an extent that on the third level of the deep Capote workings the shaft can only be kept open by maintaining a passage-way around it. In the bottom of the mine the tops, sides and bottoms of the drifts are squeezed together, like those of a tunnel run into a bank of plastic clay. One peculiarity of the low-grade ore-bodies is, that

although the rock may have lost its pristine character and may be as soft as stiff putty, the pyrite distributed through it is unoxidized and bright, even on its surface.

The ore from the Capote and Oversight mines comes to the concentrator and smelter mostly as whitish-gray clayey "fines." In the concentrator the Oversight ore in particular gives trouble, because it "thickens" the water, thereby preventing the mineral from separating out. On the concentrating-tables, garnets and similar minerals, characteristic of contact-metamorphism, are noticeably inconspicuous. At Puertocito the mineralized porphyry taken from one of the shafts "slacks" in the air to a powder.

That white feldspathic porphyry, similar to, if not identical with, that of *La Sierra de la Cananea*, may be itself a highly cupriferous mineral-bearer, is evidenced by the deposits at Ajo in southern Arizona, not far northwest of La Cananea. Here masses of mineralized porphyry form hills within a basin of other eruptive matter. The rock is pyritic throughout, and in places the ore is identical with that of the Capote basin. I noticed no sedimentary rocks at Ajo. The ore-bodies are porphyry, carrying pyrite, with chalcocite, and other cupriferous minerals.

At Clifton, also, notably on Metcalf hill, the mineralized porphyry, constituting the ore-bodies of the Arizona Copper Co., is of similar nature, if not the same, as that of Ajo and La Cananea. And the same may be said of the rock in which lies the large pyritic body of Iron mountain, in California.

For the reasons above given, and without wishing to disparage the statements of such an eminent and accomplished geologist as Mr. Weed, I question the propriety of describing the large copper-producing ore-bodies of La Cananea as a type of contact-metamorphic deposits. The porphyries have certainly taken a more important part in the genesis of these cupriferous deposits than that which he has assigned to them. At Puertocito, as well as in the Capote basin, it would seem to be more in accord with the facts to assume that the pyritic minerals brought up by the porphyry became, through magmatic differentiation, more concentrated in certain localities than in others, and that these heavily mineralized portions were very susceptible to attack from atmospheric waters. In the Capote basin,

where the mineralization was the greatest, the porphyry yielded readily to decay, the result being the formation of ferric masses (gossan), which were left on or near the surface, and the concentration of the copper below in the form of chalcocite. The gossan found on the top of the ground is a fairly good flux, and is used as such; but it becomes more and more siliceous with depth, until it rests on the ore. It presents an irregular bottom-limit, penetrating the ore in places. Immediately under the gossan comes the chalcocite-bearing porphyry. At the junction of the two, native silver is sometimes found. The workings in this portion of the Capote mine were very hot; and the more it was attempted to ventilate them, the hotter they became. Quartz-sand also (used for building-purposes) was found in this zone.

The subject of the formation of chalcocite ore-bodies by the oxidation of pyritic minerals and subsequent precipitation of the copper sulphide on deeper-lying, unaltered ore, has been handled in such a masterly manner by Mr. H. V. Winchell, of Butte,* that it would be superfluous to go further into the matter here.

There are contact-metamorphic deposits at La Cananea; but they were of comparatively subordinate importance in connection with the output of copper in 1901, and they are still subordinate. The main ore-deposits are concentrations in the porphyry of chalcocite derived from cupriferous pyrite, which came up as an accessory component of the original rock.

A correct diagnosis of the genesis of an ore-deposit is of more than scientific interest; it is of great economic importance. A better appreciation of this truism by those in responsible charge of mining operations would result in the saving of vast sums of money which are uselessly expended at the present time.

In regard to the occurrence of arsenopyrite in, or close to, contact-metamorphic deposits, the case of Sacrificio mountain, in Durango, might be cited in addition to those mentioned by Mr. Weed. These deposits, which are typically contact-metamorphic in the sense given the term by Mr. Weed—"zones of altered sediments about igneous intrusions"—are associated with veins of arsenopyrite.

* *Engineering and Mining Journal*, vol. lxxv., p. 782.

No. 14.

Ore-Deposition and Vein-Enrichment by Ascending Hot Waters.

BY WALTER HARVEY WEED, WASHINGTON, D. C.

(New Haven Meeting, October, 1902. *Trans.*, xxxiii., 747.)

THE enrichment of mineral-veins as a result of the migration of material from an upper oxidized or disintegrated part of a vein to a lower level, where it is redeposited, is now, I believe, quite generally accepted as one explanation of the occurrence of bonanzas in gold- and silver-veins, as well as that of bodies of high-grade ores in cupriferous deposits.* Vogt has called attention† to the fact that there are numerous examples of such rich shoots which are "of exclusively primary character, and dependent upon the laws which governed the original ore-deposition." To this I would add that there are also other examples which are neither of primary origin nor due to descending waters, but result from a reopening of the veins and their penetration by ascending heated waters whose metallic contents are deposited by reaction with the primary pyrite (and possibly other minerals), forming "secondary" enrichments.

My studies of the copper-veins of Butte, Montana, show: That the veins there are of several ages and systems; that the older primary quartz-pyrite veins were reopened by later movements, correlated with a period of volcanic activity; and that they were penetrated by hot alkaline waters carrying copper and arsenic in solution, which were deposited presumably by reaction with the pyrite of the original vein.

The enormous development of the Butte deposits, attendant upon the extraction of nearly 10,000 tons of ore a day, has revealed many facts concerning the nature and distribution of the ores. Enargite, the copper sulpharsenate, formerly a relatively rare mineral, is now found to be the chief ore of some veins,

* Weed, "Enrichment of Mineral-Veins by Later Metallic Sulphides," *Geol. Soc. Am. Bull.*, vol. xi., pp. 179–206.

† "Problems in the Geology of Ore-Deposits," *Genesis of Ore-Deposits*, p. 679; also, *Trans.*, xxxi., p. 168.

and to constitute a large part of the high-grade ore of the eastern properties. Its distribution is peculiar, and its significance can only be understood as a result of detailed study, but several facts stand out prominently, viz.: It occurs in immense ore-bodies, connected with faults, extending from the oxidation zone to unknown depths in some veins. But, in most cases, it first appears in deep-level workings. This ore was recently found in the 2000-ft. and 2200-ft. level of several mines; it is clearly younger than the pyritic ores, but older than the great glance ore-bodies, and is formed in small quantity in later fault-veins.

In the discussion of the genesis of the Butte deposits with the late Clarence King, he at first combated the principle of secondary enrichment, and adduced the presence of enargite as a conclusive argument against it. The later discovery of masses of brecciated enargite cemented by glance proves the enargite to be of earlier formation; and though the pyrite is the only possible source of the copper and arsenic in the original vein, numerous assays showed almost total absence of arsenic from these ores. In brief, all the evidence showed that enargite, though not a "primary" vein-mineral of the original vein, did not come from descending solutions, but must have come from below.

The bonanza-ore of Neihart, Montana, has been described by me as an example of secondary enrichment by descending waters. In the light of a riper experience and the experimental work of Dr. Stokes, it appears possible that the pearceite (arsenical polybasite) ores result from uprising alkaline solutions, though later descending solutions, carrying material derived from the oxidation of the ores, have to some extent complicated the situation. At any rate, it is difficult to account for the large amounts of arsenic necessary for the formation of these ores by the oxidation of very large amounts of primary pyrite almost devoid of this element; and it is known that arsenic occurs elsewhere in hot-spring waters, as at La Bourboule, France,* and in the Yellowstone Park.†

* Hague, "Notes on the Deposition of Scorodite," *Am. Jour. Sci.*, xxxiv., 3d ser., Sept., 1887, p. 171.

† Weed and Pirsson, "Sulphur, Orpiment and Realgar in the Yellowstone Park," *Am. Jour. Sci.*, xlii., p. 401, 1895.

Gooch and Whitfield, "Waters of the Yellowstone," *Bull.* 47, *U. S. Geol. Surv.*, p. 44 *et seq.*, 1888.

Recent experiments made in the U. S. Geological Survey Laboratory, by Dr. H. N. Stokes, show that metallic sulphides are reduced and precipitated from alkaline solutions of the general character of hot-spring waters by *pyrite*. The metallic substances may be assumed to be present as oxides of zinc, copper, lead, etc. The reaction with the alkaline waters alone is represented by the equation:

$$8\,FeS_2 + 15\,Na_2CO_3 = 4\,Fe_2O_3 + 14\,Na_2S + Na_2S_2O_3 + 15\,CO_2.$$

In the presence of a metallic oxide reacting with Na_2S, *e.g.*, ZnO, PbO, etc., the equilibrium will not be reached short of total decomposition of FeS_2, and we get

$$8\,FeS_2 + 14\,ZnCO_3 + Na_2CO_3 = 14\,ZnS + 4\,Fe_2O_3 + Na_2S_2O_3 + 15\,CO_2.$$

These are the only products present, and the reaction is complete with excess of $ZnCO_3$. The formation of Fe_2O_3 by action of a metallic salt on FeS_2 and the formation of thiosulphate have not been previously known. The latter was proved beyond question by qualitative and quantitative methods, and there is no evidence of the formation of sulphites. Pyrite and marcasite, with CuO in bicarbonate solution, react as follows:

$$2\,FeS_2 + 6\,CuCO_3 + 2\,KHCO_3 = 3\,Cu_2S + Fe_2O_3 + K_2SO_4 + 8\,CO_2 + H_2O.$$

Experiments with both pyrite and marcasite at 200° C. show that the theoretical amount of sulphuric acid is actually formed.

That such waters actually occur in nature is not absolutely known. The Yellowstone Park waters are, however, nearly of this character, and several springs at the Norris Geyser Basin are actually depositing the red and yellow sulphide of arsenic, and one case auriferous pyrite.* The Boulder hot springs, where mineral-veins are now in process of formation, in which small amounts of copper, gold and silver are deposited, are dilute solutions of alkaline waters.†

From my study of the waters and veins of the last-named

* Weed and Pirsson, *Am. Jour. Sci.*, xlii., p. 401, 1895.

† Weed, "Mineral-Vein Formation at Boulder Hot Springs, Montana," *21st Ann. Rept., U. S. Geol. Surv.*, Part II., p. 233, 1900.

locality, I am led to the following theory of primary ore-deposition:

Theory of Ore-Deposition by Thermal Springs.

Recent researches have demonstrated that openings cannot exist in the rocks which compose the outer crust of the earth at depths of 30,000 feet or more, and that, indeed, under certain conditions, they cannot exist at depths very much less than that. Observations made upon deeply buried rocks, brought to the surface by uplift and erosion, are in perfect accord with these deductions, and prove that the "unknown depths" from which ore-deposits in waters are derived cannot exceed these figures. Assuming this to be true, it will probably be admitted (since heat and pressure facilitate solution), that hot waters circulating at considerable depths will dissolve and take into solution the various materials with which they come in contact. The capacity of hot water to contain such substances in solution will depend upon heat and pressure. The water will take up the less readily soluble salts only while the conditions are favorable. With less heat and pressure the solution may become saturated for any one substance, and, though still holding it in solution, be incapable of taking up any more of that substance. In this unstable condition a slightly lessened pressure and heat would bring about precipitation.

For this discussion it does not matter whether the hot waters are of igneous, or of original meteoric origin, since they are admittedly *hot* and traverse the deep-seated rock.

In an ideal hot spring, the circulating waters slowly traversing heated, but solid, igneous rocks, out of which they dissolve various substances, flow toward the point of easiest escape, which is the hot-spring fissure. For convenience, we will assume this fissure to be straight, one thousand or two thousand feet deep, and the waters to move upward very slowly. In its lower part, as in the pores of the adjacent rocks, heat and pressure are very great and the waters are not saturated, even for the most insoluble substances, and no minerals are deposited. Nearer the surface diminished heat and pressure make the water incapable of taking more of the less soluble materials in solution, forming what may be conveniently called the zone of saturation. Some salts, like alkaline sulphates, etc., are extremely soluble, and the point of saturation is scarcely ever reached in

nature, even at the earth's surface. Others, like silica, may be present in such amount as to saturate the water, but the solution is clear until cooling and relief of pressure cause supersaturation, and precipitation occurs; an example of this was seen at the Opal and the Coral Springs of the Norris Geyser Basin, in the Yellowstone Park. Still higher in the hypothetical hot-spring pipe, diminished heat and pressure cause the separation of the less soluble constituents, and for such materials this part of the tube is the zone of precipitation. It is well known that the metallic sulphides are soluble in alkaline solutions under heat and pressure, but examples showing their deposition by living hot springs are extremely rare. The more soluble substances will be carried farther upward before precipitation, and one might even suppose, if the solubilities of the substances were sufficiently unlike, that zones would be formed, each one of which consisted mainly of the particular substance thrown out by the change of pressure. This would produce an orderly distribution of the ores in a vertical direction. This, indeed, has been observed frequently. Chamberlin records it for the lead- and zinc-deposits of Wisconsin, and Rickard* for those of Colorado and elsewhere. In the writer's own experience the order appears to be galena on top, passing into highly zinciferous ores below, and this into low-grade pyrite.† It is a common experience to find this association in silver-lead deposits in limestone. This would account, also, for impoverishment in depth and the passing into the ever-present and readily deposited silica.

The conditions in a hot-spring tube are admittedly those postulated, *i.e.*, lessening heat and pressure as the surface is approached; the assumptions made are natural ones. This, then, would explain why hot springs do not deposit metallic sulphides at the earth's surface. Owing to their relative insolubility these are deposited (if present in the water) at depths below the surface. The Sulphur Bank quicksilver mines of California are examples. At the surface they showed only

* T. A. Rickard, *Trans. Inst. Min. and Metal.*, London, vol. vi., 1899, p. 196.

† Weed and Pirsson, "Castle Mountain Mining District, Montana," *Bull.* 139, *U. S. Geol. Surv.*, 1896. Also abstract in *Jour. Geol.*, vol. v., p. 210, 1897.

Weed, "Geology of the Little Belt Mountains, Montana," 20*th Ann. Rept.*, *U. S. Geol. Surv.*, Pt. III., pp. 271–461, 1901.

sulphur and no quicksilver. In depth, quicksilver-ores appeared. Were these springs to die out and degradation to remove the upper 200 feet of the ground, quicksilver-veins would be exposed. It is probable that somewhat analogous conditions may exist at many hot-spring localities, and that if we could expose the lower part of the conduit we should find ore-deposits. This is the theory which the writer at present holds as to the genesis of the silver-gold-veins of Lump Gulch and other mining districts of Jefferson county, Montana, and which he believes is a rational ascension theory. All secondary alterations are here excluded, these remarks applying only to the primary vein-filling. It is lateral secretion only in the very special and limited application of that term to the leaching of relatively deep-seated rocks, and the gathering of such waters in a hot-spring conduit.

The close resemblance in nature and occurrence of these Boulder hot-spring veins to the jasper reefs of Clancy, Lump Gulch and many other mining districts in the granite area of Jefferson county, Montana, has already been stated. It may be accepted as certain that they also owe their origin to hot springs, and that the ore-deposits of such veins were formed by hot waters.

Theory of Enrichment.

Applying these conclusions to the question of vein-enrichments, it is first necessary to recall that bonanzas and rich ore-shoots are very frequently associated with brecciation and recementation of the vein-filling. Where the evidence precludes "secondary" enrichment from above, the possibility of enrichment by a new or renewed supply of hot water coming up the newly-formed fracture must be considered. The successive reopening of veins was formerly an accepted explanation of an orderly sequence of mineral crusts, implying a repeated uniform reopening. Such exceptional cases may occur, but it is certain that many veins occupy fissures that are lines of weakness in successive periods of earth movement. Even in the deposits still forming at Boulder Hot Springs, Montana, the veins have been fractured and the fragments cemented by newly deposited silica. At Butte and Neihart the veins have been broken by post-mineral fractures with later deposition of rich ores. The evidence at Butte (furnished by rock-walls, de-

posited ore and structural conditions) shows that the primary quartz-pyrite veins were broken by fissures that became the conduit for ascending hot alkaline waters. Such waters would tend to deposit any burden of metallic salts in zones as already outlined; they would also be influenced by the existence of the crushed pyrite of earlier deposition, which is an energetic reducing-agent.*

Dr. H. N. Stokes has continued his painstaking experimental work on the action of pyrite and marcasite, and the bearings of his results upon the chemistry of ore-deposition are of very great importance. It is well known that almost all hot-spring waters contain alkaline carbonates in solution. In an unpublished abstract of his report, which I have his permission to quote, he says:

"*Behavior of Pyrite with Carbonate or Bicarbonate Solution.*

"The reaction is as follows in case of either pyrite or marcasite and Na_2CO_3 or $KHCO_3$, at 100° or 190°:

$$\text{"8 } FeS_2 + 15\ Na_2CO_3 = 4\ Fe_2O_3 + 14\ Na_2S + Na_2S_2O_3 + 15\ CO_2.$$

"The reaction is reversible, as far as the sulphide is concerned, and is more complicated than represented, because some alkaline polysulphide is formed. Being reversible, it is not possible to prove satisfactorily the presence of Fe_2O_3 in the solid residue, but the solution was shown to contain Na_2S, Na_2S_x and $Na_2S_2O_3$.

"If, however, the sulphide be removed as fast as formed, the reaction proceeds to an end, giving, finally, only Fe_2O_3, while the thiosulphate accumulates in the solution. This can be accomplished in several ways:

"(a) A circulating alkaline solution, carrying away the sulphur as sulphide and thiosulphate, would leave the pyrite or marcasite ultimately as Fe_2O_3 or its hydrate. This can hardly be effected in the laboratory on account of experimental difficulties.

"(b) The addition of a metallic salt capable of precipitating the sulphide as fast as formed allows the reaction to proceed to an end. This is what occurs in the above reaction with lead and zinc:

$$\text{"8 } FeS_2 + 14\ PbCO_3 + Na_2CO_3 = 14\ PbS + 4\ Fe_2O_3 + Na_2S_2O_3 + 15\ CO_2,$$

and also with copper and silver (modified by the further conversion of thiosulphate into sulphide and sulphate):

$$\text{"8 } FeS_2 + 14\ Ag_2CO_3 + Na_2CO_3 = 14\ Ag_2S + 4Fe_2O_3 + Na_2SO_4 + 15\ CO_2.$$

"(c) Since CO_2 partially decomposes soluble sulphides, we actually have a portion of free H_2S, which may be volatilized, thus enabling the reaction to proceed to an end. By heating FeS_2 with $KHCO_3$-solution in a sealed vessel filled with CO_2, and so arranged that the volatilized H_2S is continually taken up by an ab-

* H. N. Stokes, "Pyrite and Marcasite," *Bull.* 186, *U. S. Geol. Surv.*

sorbent, it was found possible to convert FeS_2 completely into hematite, without direct contact with metallic salts and in absence of oxygen. The same experiment was made with artificial amorphous Fe_2S_3, which can be converted into Fe_2O_3 by long boiling with water, H_2S escaping.

"It would seem from the above:

"1. That the conversion of FeS_2 into Fe_2O_3 is not a necessary proof of the action of oxidizing (descending) waters, but may be due to any alkaline solution free from oxygen.

"2. The circulating solutions which have acted on FeS_2 may carry away alkaline sulphide, and cause the deposition of other sulphides, as of copper, zinc, lead, silver, at another place."

These reactions apply to enrichment produced by ascending alkaline waters, such as those characteristic of the Yellowstone Park, Boulder Hot Springs, and many of the hot springs of the Rocky Mountain region.

If the hot ascending waters were *acid*, a different set of reactions, determined by Dr. Stokes' work, explain the solution of gold, silver and copper from minerals of the original vein-filling, and their deposition at a higher level on cooling.* The reaction is possible with a neutral solution, but not an alkaline one.

Conclusions.

1. Ascending hot-spring waters, if metalliferous, may deposit different ores with an orderly vertical distribution. Existing veins now mined often show this arrangement of metallic sulphide.

2. Ascending hot *alkaline* waters coming up through crushed and reopened veins containing pyrite (or marcasite) react with this sulphide, and zinc, lead, copper or silver, if present, is thrown down as sulphide.

3. Ascending hot *acid* waters may leach the lower levels of reopened veins and deposit gold, silver and copper upon cooling at higher levels.

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* The full results of this very important experimental work of Dr. Stokes will soon be published. See, also, by him, "Pyrite and Marcasite," *Bull. 186, U. S. Geol. Surv.*

No. 15.

Basaltic Zones as Guides to Ore-Deposits in the Cripple Creek District, Colorado.

BY E. A. STEVENS,* VICTOR, COLO.

(New York and Philadelphia Meeting, February and May, 1902. *Trans.*, xxxiii., 686.)

IT has been ascertained in recent years that certain rock-types, geological formations and structural conditions may be used as fairly reliable guides, when prospecting in recognized mineral belts or mining districts, with a reasonable certainty of discovering "pay-ore;" and that such is considered as a practically established conclusion may be inferred from a perusal of the recent reports of the U. S. Geological Survey and the literature of the several scientific societies discussing mining, geology, and kindred subjects.

Cripple Creek is no exception to this conclusion, and the rock-type or association, rather than the structural condition, is the most infallible guide.†

These guides consist of four, possibly five, dike-rocks, three of which are extremely basic, while the fourth is an acid rock of an entirely dissimilar character. The basic rocks are nepheline-basalt, limburgite, feldspar-basalt and tephrite. There are grounds, however, for believing that the two latter are subdivisions of one type, and therefore will be described under one head. The acid rock is quartz-porphyry.

Nepheline-basalt is a rock encountered in but few localities elsewhere on this continent, and occurs in narrow dikes cutting various formations. When typical,‡ it is composed of

* Died January 31, 1902. The manuscript of this paper was received only a few days before his untimely death.

† The writer will not deny that in a very few instances there is apparently a relation existing between a late, extremely basic andesite and ore-deposition, but is very confident that sufficient development will demonstrate, as in similar cases heretofore, that these deposits are more closely allied to basaltic dikes or zones.

‡ The nepheline-basalt of this district is not a typical rock; for instance, the dike extending northward from Battle mountain, along the east side of Arequa gulch, contains glass, much megascopic biotite and plagioclase, and is remarkably poor in nepheline. This condition confirms the opinion of the writer, expressed in a previous paper (*Trans.*, xxx., 763), that much of the so-called nepheline-basalt is limburgite.

nepheline, augite and olivine, with hornblende, mica, and, rarely, plagioclase, as accessories. In this district, however, it may contain all of the above, with the addition of magnetite.

Limburgite, which was positively identified in this district quite recently, is a rock closely allied to nepheline-basalt, both structurally and chemically. It is composed of a glassy ground-mass, containing large and small augites, magnetite, abundant megascopic olivines, and some mica, shading locally into a variety, verite. It also here contains the rare accessories, plagioclase and, occasionally, nepheline.

The last of the basic rocks, usually referred to as feldspar-basalt, is probably tephrite,* as nepheline, which is present microscopically, is too abundant locally to be considered as other than an essential constituent. This rock is composed of plagioclase, augite, and some nepheline. The accessories here are biotite, magnetite, apatite, titanite, an undetermined mineral which is probably sanidine, and, rarely, olivine.

The one dike of quartz-porphyry, with its few branches, is unique in its occurrence. It was casually referred to by Dr. Cross in Part II., Sixteenth Annual Report, U. S. Geological Survey, and has otherwise escaped observation. (See Fig. 4.) It has a very compact, bluish-black ground-mass, composed of orthoclase, much plagioclase, quartz, and some augite or other dark silicate. The structure is distinctly tabular-jointed. Scattered through the ground-mass are a few double-terminated, greasy quartz-crystals, and an occasional phenocryst of orthoclase or sanidine. Physiographically, it, like the tephrite, resembles the nepheline-basalt and limburgite. These rocks, as dikes, comprise the later intrusions; nepheline-basalt and limburgite were contemporaneous, and probably the last extruded.

These dikes cut all the earlier formations of the district. The latter, with the exception of granite, schist and diabase, are generally classed, by the miners, as "porphyry;" they really consist of andesitic and phonolitic tuff and breccia, massive and dike andesite, phonolite, trachytic-phonolite, nepheline-syenite, and, in two instances, trachyte. Owing to the early

* No nepheline is present in the dike of the Seavey shaft on Block 7 of State land; but in the same dike, where exposed by the 40-ft. shaft of the "Little Daisy" mine, the higher power of the microscope reveals many crystals in each slide.

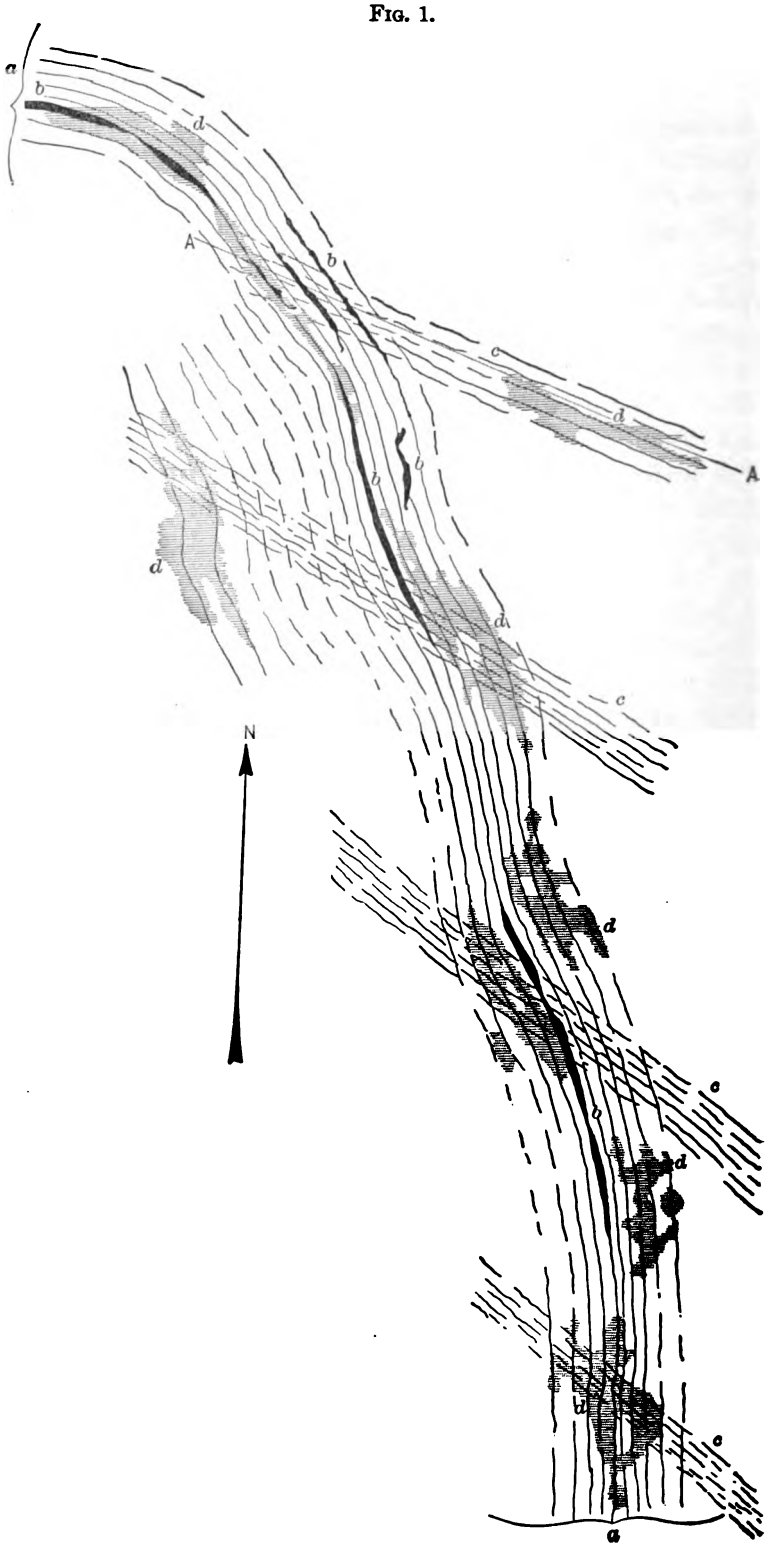
decomposition of the basalt and limburgite upon exposure to the atmosphere, these dikes, with one exception of limburgite, form no outcrops; nor have they, except on very rare occasions, been found in a sufficiently fresh condition for determination. The same is also true of the tephrite. The two former, when fresh, are very compact, of a greenish-black color, showing only phenocrysts of olivine, except the verite, which contains many crystals of biotite an inch or more in diameter. The tephrite exhibits a compact ground-mass, containing megascopic phenocrysts of augite and plagioclase.

The structure of each basaltic rock, when fresh, is jointed, and the fracture, when broken transversely between joints, is conchoidal. The first stage of decomposition is a zeolitization along the joint-planes, which is soon followed by devitrification, and, subsequently, a breaking down of the entire mass, finally resulting in serpentine.

The practical importance of the presence of these rocks cannot be overestimated. It is not intended to convey the idea that at every point at which one of these dike-rocks may be exposed, ore is, or will be, found in paying quantities. It is a well-established fact that the ore occurs at varying intervals along the veins in the form of "shoots" or "chimneys," often separated by thousands of feet of barren vein-matter. The assertion is sometimes made that there is not a profitable mine in the district that does not show either the presence of one or more of these dike-rocks or a certain direct relation existing between them and the ore. This relation may be explained thus: The fissures to which the dikes belong are approximately parallel and occur in systems, and one or more of the fissures may contain the dike or dikes, which are very erratic; and it has frequently been observed that the dike-bearing fissures may be devoid of filling for hundreds of feet in depth and thousands of feet in length. These fissured zones often, although not always, extend entirely across the district,* and are

* The Beacon hill mines are on a direct line with some of the limburgite dikes that cut Gold hill in a northerly and southerly direction, and are unquestionably on the same zones. The writer has traced one fissure, which contains the western branch of the basaltic mass at the Dolly Varden mine, southward through Raven, Guyot and Beacon hills, and has observed ore along it at no less than ten different points. A like condition prevails regarding the position of the mines on the north slope of Bull and the east slope of Ironclad hills, with reference to the basaltic zones to the southward.

FIG. 1.



Showing the Structure of the Ore-Zone.
a, Fissured zone. *b*, Basalt. *c*, Ore-shoots. *d*, Cross-fissures.

from 100 to 1200 ft. wide. The zone comprises hundreds of fissures (many of which are often detected only by the aid of a powerful microscope), separated at times by microscopic bands, and at others by many feet, of country-rock. The veins and their ore-deposits may occur either in the dike-bearing fissure, including the dike, or any other fissure or fissures of the zone. (See Fig. 1.)

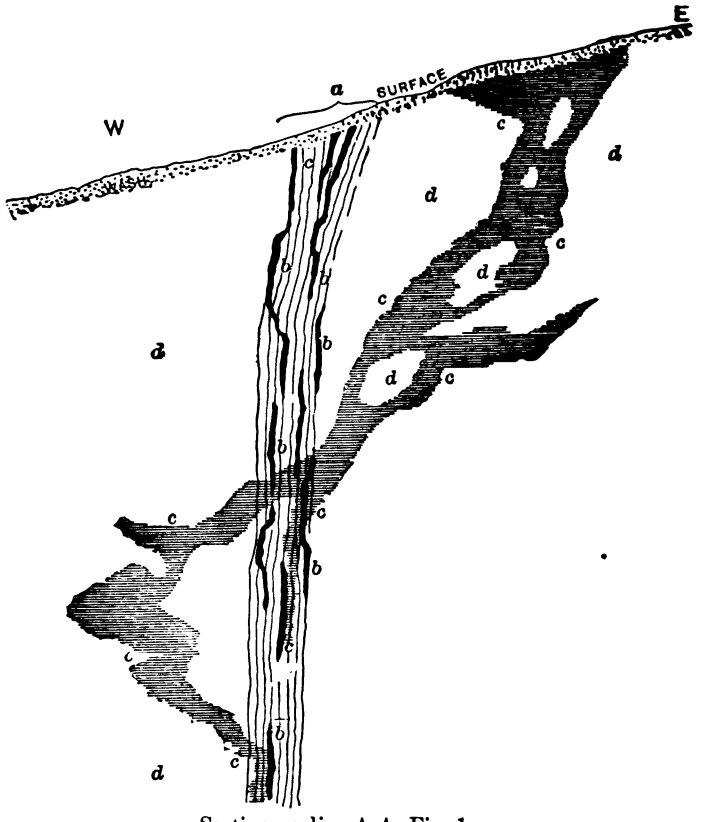
It may be inferred from an examination of this figure that the ore-deposits should be more properly assigned to the cross-veins, as the greater number of the "shoots" or "chimneys" occur at the points where these intersect the main veins. This condition will be briefly explained for the benefit of those who are not familiar with the local characteristics of ore-deposits. It will be readily understood that at these points of intersection the channels for water would be more open, and the solutions containing the minerals would meet with much less obstruction to circulation than if there was but one system of fissures or fractures, and would, consequently, spread over areas and follow lines of least resistance. Comparatively speaking, our studies and observations are but superficial, and we may not judge of the conditions farther down in the earth (where is presumed to be the ultimate source or turning-point of the mineral-bearing solutions); we can observe them only as they approach the surface. There are instances where veins crossing the main fractures at a high angle contain the only known shoots, which reach the surface hundreds of feet away from the points of intersection. But in sinking upon or developing these "shoots" in depth, it is found that they gradually, though persistently, approach the point of crossing with the main system in their downward course; and in many instances they have been found to pass through the intersection, return to it, and then follow the main system to as great a depth as developed. (See Fig. 2.)

These are the zones, therefore, that must be discovered before permanent mines can be opened up; but, as usual, the difficulty lies in distinguishing those which are likely to prove productive.

Dikes of considerable thickness maintain their individuality through the various stages of decomposition and alteration, independent of their environment, while the very thin dikes pass

into the hydrous silicates of magnesium or aluminum, forming the ordinary so-called "talc" of our veins,—under which condition, from a practical standpoint, identification becomes impossible. Another obstacle to the determination is the extreme

FIG. 2.



Section on line A-A, Fig. 1.
a, Fissured zone. *b*, Basalt. *c*, Ore-shoots. *d*, Cross-fissures.

secondary silicification to which not only the dikes themselves, but the entire area of eruptive rocks have been subjected.*

* It has recently been stated that the proximity of the veins, while conducting exploration-work in this district, may be recognized by an increased silicification, which reaches its maximum at and through the veins. A very casual examination of the surface of this region will suggest the untenability of this position. The veins of this district have eroded away proportionately to the enclosing breccia and granite; no more nor no less. If they were silicified to an extreme or even an unusual degree, comparatively, they would form sharply-defined ridges against the breccia or granite background; while, if silicified to a less degree, gulches, hollows or depressions would mark their apices.

Moreover, it is not always possible, with limited development, to determine to what extent the intrusions may be apophyses, which many of the so-called dikes of these basaltic rocks have proven to be. Under such conditions the accompanying ore-deposits, if any, correspond in amount to the dike-matter, as will be instanced later on. This district has been subjected to many disturbances, both orogenic and volcanic, as is indicated by the many faults, fractures and displacements in and surrounding the locality, and the variety of ejectamenta thrown out by the volcano. The disturbances may have been confined to one period, but that period must have been divided by long intervals of time.

Each movement had its own system of fissures, often intersecting the preceding system at a low angle, and its distinct type of lava to fill those fissures.

It is proper at this time to state that the pre-Tertiary fissures, most noticeable in the southern portion of the district, have no observable connection with the Cripple Creek volcano, and, when filled with dike-rock, the filling is of diabase.

For reasons which have already been given, it is known that the rocks referred to as guides represent the latest lava extruded by the volcano.

It is also positively known that ore-deposition occurred subsequent to the latest eruption or intrusions, as mineralization has occurred through and along the latest dikes where they are intersected, crossed or followed by the fissures which form the veins. And it is a significant fact that these later fissures, while occurring almost independently of the dikes, seem to belong to the same general fissured zones, and doubtless represent shrinkage-cracks, probably along lines of weakness resulting from the contraction of the mass upon cooling, immediately following the intrusion of the dikes. These cracks were further enlarged, individualized and intensified by faulting-movements, which unquestionably are responsible for transportation, localization, and probably, to some extent, deposition of the ore.

It has been argued by some that the later dikes cut the veins, and that at the points of intersection for the full width of the dikes no ore could be found. This opinion, it is believed, is formed from a lack of careful investigation and study, and

an improper appreciation of circumstances and surroundings. Existing conditions do not warrant such a belief or confirm such an opinion.

The most prominent instance upon which this argument is based has been thoroughly investigated by the writer, physiographically, chemically and microscopically. It was thereby positively determined that the rock in question is not a Tertiary basalt, but an ancient diabase. Several years ago (owing to its extreme decomposition and alteration and the position which it occupies, being near the contact between the breccia and granite) it was mistaken for andesite. It is also inferred, from such investigation, that the rock was so highly altered long prior to the circulation of the ore-bearing solutions that none of the necessary reagents for precipitation had been retained; nor could it, in its condition, maintain the temperature presumed to be necessarily attendant upon ore-deposition.

It is not to be expected that the fissures would maintain their individuality through a decomposed, crumbling formation, although considerable silicification might characterize the mass locally.

It has further been urged, in support of this theory, that the deposits, admitting that such occur, through and along dikes, are "secondary enrichments" from decomposition and leaching of the ores from the lateral points where the veins have been cut off by, and adjoin, the dikes; but no explanation is offered by its exponents as to why the fissures extend uninterruptedly through the dikes, where in a sufficiently preserved condition to support them.

The latter argument is not logical, as the deposits occurring in the dikes are composed of sulphides and tellurides, corresponding in every particular with the veins before entering or crossing them. And even if these fissures and veins, containing ores consisting of the original minerals, did not extend through the dikes, the explanation would be that the dikes were still in a plastic state when the fissures were formed, all evidence of which would then become obliterated when the lava solidified. There are instances, to be sure, where the original gold-bearing minerals to be seen in the dikes have become much more oxidized than in the enclosing country-rock; but this condition should be expected in all basic rocks, owing

to their many easily-destructible constituents. In the quartz-porphyry, however, the sulphides and tellurides show the effects of oxidation much less than in the enclosing breccia and phonolite, although this dike is characterized by both augite or pyroxene and plagioclase.

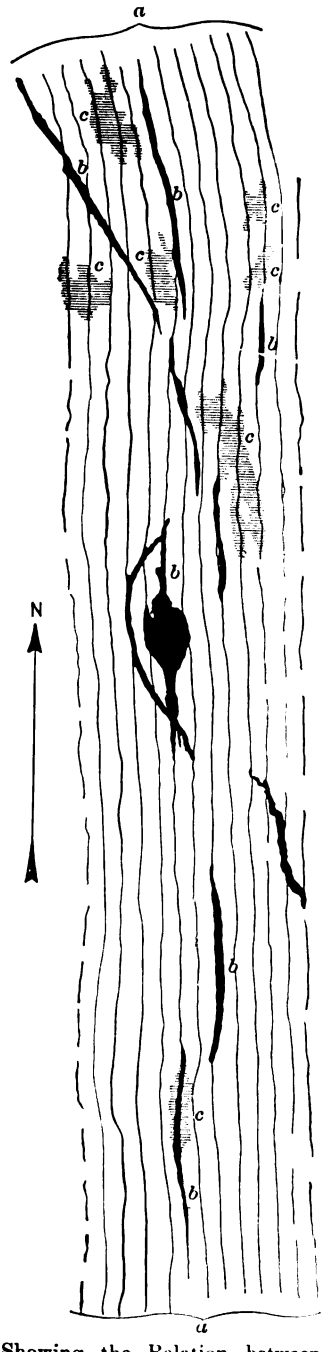
The following mines, with which the writer is familiar, having been connected with them professionally or otherwise, will be cited as examples in support of the arguments advanced in this paper:

1. In various "workings" of the Portland, Independence, Strong, Dillon, Monument and Granite mines, upon Battle mountain, there is a zone containing several distinct nepheline-basalt dikes, all having a general northerly and southerly course, and many short, lenticular* masses or "plugs" of the same basalt, often wholly altered or heavily mineralized, forming locally good ore. This zone is about 1200 ft. wide.

2. The May Belle Tunnel, Gold Coin, Ajax, Dead Pine, Triumph, Coriolanus and Carbonate Queen mines, upon the same mountain, are penetrated or crossed by dikes of limburgite, or the fissured zone to which the dikes belong. This zone is about 600 ft. wide, and a broken, erratic dike of limburgite extends along it, having a N. and S. course. Near the southern extremity of the zone one of the fissures is filled with verite for a dis-

* Inclination with dip of veins, in all cases herein cited.

FIG. 3.



Showing the Relation between Limburgite and the Ore-Zone. *a*, Fissured zone. *b*, Limburgite. *c*, Ore-shoots.

tance of several hundred feet. Near the center of the zone, transversely, occurs a small vent or crater, filled with limburgite. (See Fig. 3.) The dike splits near the Ajax mine, the branches separating, and the principal one veers slightly to the northwestward, passing through Eclipse ground near Arequa gulch, and into the Moose mine on Raven hill.

3. The Thompson, Elkton, Raven and Tornado mines, located upon Raven hill, have their workings in and along nepheline-basalt dikes, the entire thickness of which, at times, comprises the ore-bodies.

4. The Pointer, Midget, National and Moon-Anchor mines, all upon Gold Hill, save the National, are situated upon a narrow-fissured zone, having a NNE. course. One strong dike of limburgite which enters them is traceable for a half-mile through the granite to the southward. Near the contact (between the granite and breccia) the dike is scattered by a quartz-porphyry dike, which it then follows. A few hundred feet to the northeast of this point it again becomes well-defined and passes to the northward. In the northern portion of this zone occur several parallel dikes of limburgite.

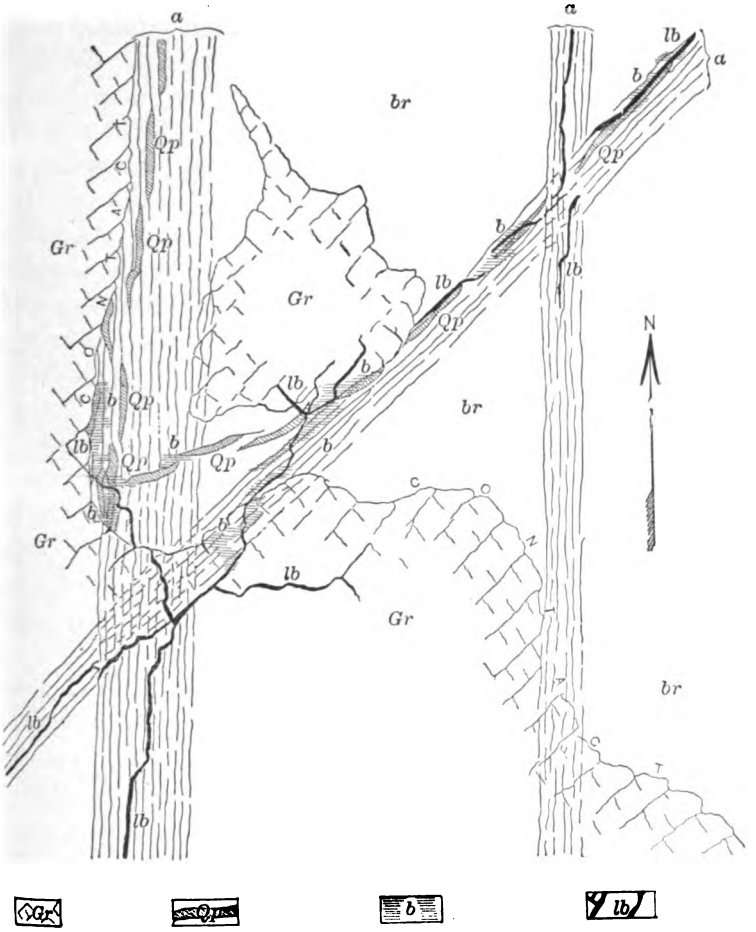
It has very recently been discovered by the writer that the ore-deposit worked through the National mine is associated with one of the late igneous eruptives. This mine is located on a narrow easterly and westerly fissure-system in the granite, some 500 feet west of the westernmost fissure of the north-south zone. The condition of the few lens-shaped masses of basaltic rock (which is limburgite), conforming to the fissure-cavities, stamps this occurrence as an apophysis. This supposition is also borne out by the fact that the ore-body was very limited.

5. The Red Spruce, Accident, Mint, Union Belle, Hillside, Moonlight and Anchoria-Leland mines, on Gold Hill, are penetrated by, or have their ore-bodies composed of, or associated with, quartz-porphyry and limburgite.* The quartz-porphyry

* The dike of limburgite following the NE.–SW. fissured zone, represented as coming in at the southwest corner of Fig. 4, reaches across, diagonally, from another N.–S. fissured zone to the west. It does not cross the westernmost zone, however, but turns southward and follows it for some distance before "pinching." This N.–S. zone passes through the Gold Bond property, the El Reno mine,—famous for having produced the first calaverite-bearing ore of the district,—and its influence is next observed in the Dead Shot and Mary Nevin properties to the southward.

dike occupies one or more fissures of a zone having a course approximately northeast. This dike is much brecciated, and not as well defined as the basaltic dikes. It was contemporaneous with a movement of the country which had not entirely

FIG. 4.



Limburgite Dike in El Reno Mine.

br, Breccia. *Gr*, Granite. *Qp*, Quartz-porphyry. *b*, Ore-shoots. *lb*, Limburgite.

subsided until the dike had cooled; therefore, its continuity is broken in many places between the contact, where it has its westerly termination, and the point where it is intersected by the limburgite, described in case 4. A portion of the limburgite deviates from its regular course at this point, and subordi-

nate amounts are observed at various intervals accompanying the quartz-porphyry as far as explored. This is the narrowest zone of the several described, not exceeding 100 feet in width at any point.

The Red Spruce and Accident mines, in this connection, deserve especial mention, as they differ considerably from any other mines in the district. They are both situated on the true contact* between the breccia and granite. There are small, detached bodies of phonolite, trachyte, limburgite and quartz-porphyry present in their workings. The first two are of limited, the third of general, and the last of special, economic importance. The limburgite which appears in the Accident shaft at a depth of 240 feet crosses the contact at an approximately right angle, piercing the granite to the westward. This is an apophysis, and its individual influence is not remarkable. The quartz-porphyry follows the contact, at times, then deviates to the westward, into the breccia, following fissures parallel to the contact for 50 or more feet, and then again breaks across the formation to the contact. A branch of this dike extends northward under conditions as described, while the main dike passes to the northeast into the Mint, Union Belle and Hillside mines. The chief ore-bodies of the Accident and Red Spruce mines contain lead, silver and gray copper† (all characteristic of quartz-porphyry), some gold-bearing pyrite, also calaverite and sylvanite.

6. The Zenobia, Pharmacist, Burns, Orphan Belle, Isabella, Block 8 of State land, Free Coinage, Lucky Guss, Deadwood, Delmonico, Vindicator, Christmas and Golden Cycle mines, situated upon Bull Hill, are crossed by or associated with tephrite or feldspar-basalt.

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* A line drawn from the northeast shoulder of the contact, near the center of Fig. 4, northwestward, along the easterly side of the detached granite mass, would represent the position of the contact as described in all literature and shown on all maps of the district so far published. This is for the reason that all of the maps are copies, with a few omissions or additions, of the "Special Cripple Creek Sheet" issued by the U. S. Geological Survey. Dr. Cross, who was in charge of the field-work of the Survey, attempted to represent approximately, only, the position of the contact at this and other points.

† The superintendent of the Accident mine informs me that he found a "kidney" of gray copper-ore in a "split" in the dike (quartz-porphyry), containing about 1000 pounds, which sampled 5000 ounces silver and 50 ounces gold per ton.

7. An examination of the Victor mine disclosed lenticular masses of a basaltic rock accompanying the vein, too highly mineralized for accurate classification.

8. The same condition was observed in the Doctor-Jack Pot workings on Raven Hill; and much of the breccia, heretofore classed as "andesitic," contains fragments of basalt or limburgite.

It will be observed, therefore, that the mines which have produced 90 per cent. of the gold of this district, which has amounted to more than $115,000,000 during the past ten years, are penetrated or crossed by, or closely associated with, the various basaltic rocks and the dike of quartz-porphyry; and for these very important reasons I infer, and it appears to be both logical and proper to state, that the rock-types and association above described are the true and only guides to point out the probable course to pursue in order to open a "pay mine" in the Cripple Creek district.

No. 16.

The Geological Features of the Gold-Production of North America.*

BY WALDEMAR LINDGREN, WASHINGTON, D. C.

(New Haven Meeting, October, 1902. *Trans.*, xxxiii., 790. Part III. omitted in this republication.)

CONTENTS.

	PAGE
I. INTRODUCTION,	424
II. GEOLOGICAL FEATURES:	427
The Gold-Bearing Fissure-Veins,	427
Contact-Metamorphic Deposits,	432
Classification According to Age,	433
Introduction,	433
Pre-Cambrian Deposits,	434
Cretaceous Veins of the Pacific Coast,	435
Late Cretaceous or Early Tertiary Deposits (Central Belt),	436
Tertiary Deposits,	438
Conclusions,	442

I. INTRODUCTION.

THE precious metals, gold and silver, are the basis of the monetary systems of the world. It is, therefore, natural and inevitable that widespread interest should be manifested in their production and in the various classes of deposits in which they are contained.

At times a great scarcity of the precious metals has prevailed; at other times the production has seemed so abnormally large that fears have been entertained regarding their ultimate retention as standards of value. Since most nations have adopted the gold standard, and the remaining ones appear likely to do the same in the near future, the question of available supply of gold for the present and future very naturally arises. This necessarily involves a consideration of the characteristics of the gold-deposits.

After the absorption of the gold treasures of the New World by the *conquistadores*, the gold-placers of Brazil and Russia

* Published with the permission of the Director of the U. S. Geological Survey.

next filled the world's need; later, when these sources of the precious metal began to be exhausted, came the great discoveries of California and Australia, which for a time caused doubts to arise as to the wisdom of maintaining this metal as a standard of value; but from the maximum of output obtained during the early years a steady decline began. The uncertainties as to the amount of gold available for the future were emphatically expressed by eminent geologists and mining engineers.

After an admirable discussion of the gold-resources of the world, Prof. Edward Suess, of Vienna, in his book, *The Future of Gold*,[1] came to the conclusion that there was scarcely any hope of further considerable discoveries, and that the output would gradually decrease, so that the metal would no longer be able to maintain its present economic position.

About the same time, in 1880, Alexander Del Mar published his *History of the Precious Metals*, and arrived, in the main, at similar conclusions. He believed that not only physical devastation, but moral and political decay, follows as the result of gold-mining, and that the total supply of both metals, and particularly of gold, will continue to diminish both in the mines of the Pacific coast and in those of other countries. It seemed to him "but too evident that the future supply of these metals will not only fail to keep pace with the growth of population and commerce, but they will absolutely diminish."

There seemed, indeed, to be good reason for such conclusions, for the gold-supply of the world was steadily diminishing and no new sources seemed in sight. But these years proved to be the turning-point, and the production again began to increase, at first, however, very slowly. In 1892, S. F. Emmons, in a most valuable review of the gold- and silver-production, came to the conclusion that a further advance in the output of gold was probable; that the annual production of the United States would soon "increase to $40,000,000, and perhaps beyond;" and that the gold-production of the world would "increase to $150,000,000 within a few years, and perhaps to $200,000,000 before the close of the decade."[2] These predictions have been greatly exceeded by the results of the work of

[1] *Die Zukunft des Goldes* (1877).

[2] *Mineral Resources of the United States for* 1892, pp. 90 to 93 (1893).

the last few years. The treasures of South Africa and West Australia were found; in Alaska and British Columbia new deposits of wonderful extent were opened; and even in such presumably well-prospected regions as Colorado, California, Arizona, Montana, and Mexico, new finds were constantly reported, and the production rose steadily and rapidly.

About 1880 the world's annual production of gold was approximately $100,000,000; that of the United States about $33,000,000. In 1900 the gold-production of the world had increased to nearly $300,000,000, and that of the United States to $79,000,000. While it is true that it is easier to criticise than to predict, it may be pointed out that two principal errors vitiated the conclusions of Professor Suess and Mr. Del Mar: In the first place, the lands of the world were deemed to be so well prospected that no further discoveries were probable; the second error lies in the failure to anticipate the possibility of new processes for gold-extraction and the utilization of vast reserves of low-grade ore-bodies.

The figures of the gold-production during the last decade may indeed cause hesitation in further predictions as to the available amount of gold. As to ultimate results, it would seem as if we should be justified in concluding, with Professor Suess, that the gold-supply of the world will gradually decrease if no further important improvements are made in the processes for the extraction of this metal; but regarding events so far distant no predictions may safely be made. Regarding the immediate future, it seems likely that the present production of the world will be sustained, and possibly increased.

The purpose of this paper is briefly to consider the product of each State in North America, emphasizing especially the derivation of the gold from its various classes of deposits, so as to arrive, if possible, at an approximate conclusion as to the relative importance of the different kinds of deposits, and finally to indicate the probable outlook in each State for the immediate future. These calculations have been made possible by the aid of the reports of the United States Mint on the production of the precious metals, the character of which has steadily improved, and which afford a vast amount of important data for the student; and, further, by the reports of the official geological surveys in regard to the economic geology of the

States. Much is still lacking, more especially in the knowledge of the age of many deposits, and this paper must, therefore, be considered only as an imperfect first attempt to collect data which are at the disposition of many, but the arrangement of which has not yet, for some reason, been undertaken.

II. Geological Features.

The Gold-Bearing Fissure-Veins.

Practically all the gold-output of North America is derived from fissure-veins or from deposits which possess close relationship to fissure-veins. Gold-bearing fissure-veins are in most cases accompanied by placers, which are only the result of nature's crushing, concentrating, and refining; and these placers may be of different ages according to the date of formation of the vein. Most of them are naturally of Pleistocene (recent) or Tertiary age. For the present purpose the placers will not be considered separately, but *as belonging to the fissure-veins from which they were derived.*

The deposits in fissure-veins are believed to have been formed chiefly by ascending hot waters. The general trend of the testimony indicates that the gold is brought up from lower levels rather than derived from rocks near the surface.

Gold-bearing fissure-veins or equivalent deposits occur in practically all kinds of rocks known on the continent; it is apparently not possible to establish wide-reaching genetic conclusions on the basis of the petrographical character of the wall-rock.[3]

The influence of *locality* is much stronger. Gold-bearing veins cluster in certain localities. A critical examination will reveal the fact that many vein-systems are massed about the contacts of intrusive masses, which consolidated far below the original surface of the earth at the time of the igneous activity, and which have been exposed by subsequent erosion. Most commonly, perhaps, these intrusive rocks are diorite, monzonite, quartz-monzonite, granodiorite, or their porphyries, more rarely typical granites. Under favorable conditions it can often be proved, and in other cases established with probability, that

[3] This point has recently been emphasized by W. H. Weed in his paper, The Influence of Country-Rock on Mineral Veins, *Trans.*, xxxi., 634 (1901); p. 216, this volume.

the upper part of the vein has been removed by the same erosion which laid bare the intruded rock-masses. In other words, the top of the vein has been removed, the root remains. It seems plausible that in these cases the igneous intrusion was one, perhaps the principal, of the genetic causes. Dynamic action producing fissures in and about the intrusives is another genetic cause. The age of these veins must in general be considerable, for the great erosion involved has usually required a long time-interval.

Another large class of vein-systems cut the recent or comparatively recent lavas, which cover the surface of the older, eroded rocks in the form of successive volcanic flows. Frequently the age of these lavas may be established with accuracy. From available data we may be enabled to determine the approximate level of the surface of the earth at the time the last flow was erupted; and, in the case of veins cutting this series, we are enabled to say with certainty that a given part of the vein was near the original surface of the earth existing at the time of vein-deposition. This given part may, then, be said to be the top or the true apex of the vein.

It is true that there are very many cases in which we cannot determine with certainty, or even with probability, at what vertical distance from the part of the vein under discussion the original surface of the earth, at the time of vein-formation, was located. But this does not diminish the force of the argument in the two principal divisions discussed. There are certainly few gold-bearing districts on the continent which do not occur either near or in intrusive masses, or in or near volcanic flows. In districts of igneous activity the effusion of surface-lavas is generally accompanied by the intrusion of bodies of magma far below the surface, which, owing to physical conditions, consolidated as granular or coarsely-porphyritic rocks. This has actually been shown in many volcanic districts which have been deeply and rapidly dissected by erosion. In rare cases we may even trace the vein from the top in the effusive lavas down to the root in intrusive rocks. It may, therefore, be concluded as most probable that the two classes of veins described above are really of the same kind: that the roots reached up through once overlying, now eroded, lavas, and that the tops generally may be traced through the lavas to the vicinity of the intruded masses.

The question whether any difference exists in mineral composition and metasomatic alteration between the tops and the roots of veins is a most important one, but it cannot be definitely answered in the present state of our knowledge. There are arguments *pro* and *con*. Professor De Launay answers the query in the affirmative, and many of his arguments have great force. This much is certain: that in many cases of gold-quartz veins differences of up to 4,000 ft. in elevation have little influence on the minerals and vein-matter, while in some cases, and chiefly with smelting-ores rich in silver, distinct changes in mineral composition appear in depth, which would seem to be independent of secondary alteration or enrichment.

Fissure-veins carrying gold have certainly been formed at various times in the geological history of the continent. Cambrian conglomerates bear witness to pre-Cambrian gold-veins, and very recent thermal deposits at Steamboat Springs, Nev. (according to Becker), and at Boulder, Mont. (according to Weed), prove that gold is deposited by thermal waters to-day. But the process has evidently not been a continuous one. Cambrian, Silurian, Devonian, and Carboniferous gold-deposits are not definitely known to exist in North America. Continuous sedimentation, absence of dynamic movements, and relatively slight igneous activity characterized these periods.[4]

The great eruptions of the Cordilleran belt of North America began during the Triassic period of the Mesozoic age, and igneous activity has continued almost without interruption from that date to recent time. Each eruption has probably been accompanied by more or less extensive deposition of gold in fractures near the igneous focus. On the Pacific coast the eruptions began at an earlier date than in the region of the Rocky mountains; and, likewise, many of the gold-deposits of the Pacific coast antedate those of the Rocky mountains. In the latter province the igneous rocks began to break out at the close of the Cretaceous period, and have continued at least up to the beginning of the Pleistocene. Certain periods of deposition, however, stand out prominently, and we may with good reason separate the distinctly Cretaceous or late Mesozoic gold-

[4] Igneous rocks of Palæozoic age are found at various places along the Sierra Nevada, British Columbia, and Alaska. If Palæozoic gold-deposits are found on this continent, it will probably be along this line.

belt of the Sierra Nevada and the Pacific coast in general from the Tertiary, mostly post-Miocene, veins so extensively developed in Mexico, Nevada, and Colorado. The former are genetically connected with great intrusions of granitic and dioritic rocks, the latter with big flows of surface-lavas which erosion has not, as yet, removed. But both in the Great Basin and in the Rocky mountains there are also many deposits of late Cretaceous or early Tertiary age genetically connected with intrusions of granitic rocks and, very commonly, porphyries. In very many cases the age of these deposits is doubtful. If erosion has been exceptionally active in the particular district in which they occur, they may well, though occurring in connection with deep-seated intrusions, be of Tertiary age. To this class of doubtful age belong, for instance, many of the gold-veins of Montana. Miocene and later igneous rocks are often lacking in this region, so that an accurate determination of age becomes very difficult.

Still another complication to be borne in mind consists in possible, though probably rarely occurring, re-opening of veins and superimposition of deposits of two or several epochs. All this being admitted, there still exists, in my opinion, sufficient reason for attempting a division of the deposits according to age. It is readily acknowledged that this first attempt is imperfect, and that future researches will probably bring many changes in the divisions here tentatively set forth.

The next question is, whether there is any notable difference, in mineral constituents and metasomatic alteration, between deposits of various periods. The mineral vein is the result of two variable factors: the composition of the mineral waters and the conditions at the time of deposition. Is there any definite gradual change in both or either of those factors by which the older deposits can be distinguished from the younger?

The question of depth below the original surface has already been touched upon, and in considering the present problem it is necessary to deal with those parts of deposits of various ages which were formed at the same distance from the original surface. A definite answer is difficult because the older deposits are usually more deeply eroded than the recent ones. *A priori*, however, there seems no reason why a difference should exist, for mineral waters of as many different kinds of composition

as are seen to-day have probably always reached the surface, and the conditions of deposition at corresponding levels and under corresponding circumstances have probably always been about the same.

Looking over the field, it is undeniable that within many belts of gold-deposits of contemporaneous origin the veins are very similar in mineral composition and metasomatic development. The Appalachian belt of gold-quartz veins contains deposits of striking similarity from one end to the other. The Mesozoic gold-quartz veins of the Pacific coast are practically identical in character from Lower California to Alaska, and, moreover, closely related in character to the far older Appalachian belt. Where the wall-rocks were easily altered, they contain abundant calcite and other carbonates, besides much sericite. This points, without doubt, to a remarkable constancy throughout the whole province in the composition of the mineral waters which formed the veins. They were manifestly distinguished by an abundance of alkaline carbonates. On the other hand, scarcely one of the veins, which in so many parts of the Cordilleran region cut volcanic flows of Tertiary age, can be classed as identical with the Pacific coast type of gold-quartz veins. While it is perhaps not permissible to say that they represent one type, yet most of them have certain common, peculiar features, constituting a relationship. They frequently contain both gold and silver; the gold is finely divided, and rarely accumulates below the veins in such rich placers as are found associated with the Pacific coast type of gold-quartz veins; the metasomatic alteration is generally propylitic; that is, accompanied by the formation of chlorite, epidote, and, near the veins, of sericite and kaolin, while the extensive carbonatization found near the California gold-quartz veins is usually absent. The mineral waters accompanying the Tertiary eruption certainly differed on the whole, and notably from those of other eruptive periods, and were apparently lacking in alkaline carbonates. Professor Suess recognized this type long ago, basing his conclusions largely on von Richthofen's work. Professor Vogt has more recently insisted on its importance. There are several types of these Tertiary veins, and it is perhaps not advisable, as I have done in a preliminary note on this subject, to retain the name *propylitic* for the whole group, as some of them do not show this alteration in typical form.

In conclusion, it may be said that gold-veins of the same age and province usually have the same characteristics. Belts of different age may differ greatly in general features. This is probably due to varying composition of the mineral waters following different periods of eruption.

Possibly, as suggested above (p. 430), the depth below the original surface may have something to do with this question, as the older veins are usually deeply truncated by erosion, and a gradual change in the character of the thermal waters may have taken place during the upward passage of the solutions. More likely, however, the principal cause is a radical difference in the composition of the waters throughout the province.

In comparing different veins with a view to the elucidation of this problem only those having country-rock of similar general character should be selected, for it is well known that the composition of the wall-rock may have great influence on the metasomatic processes, and hence on the composition of the vein.

Contact-Metamorphic Deposits.

The preceding remarks apply exclusively to fissure-veins and the closely-related irregular deposits in which the gold was deposited by heated waters, which, as a rule, probably came up from below.

There is another source of gold in the so-called contact-metamorphic deposits formed at or near the contacts of intrusive granitic or porphyritic rocks. The characteristic mineral associations (ordinarily garnet, epidote, vesuvianite, ilvaite, magnetite, specular hematite, and sulphides) of these deposits are such that they are probably best explained as the products of the action of water above the critical temperature. This water is believed to have been given off from the hot magma, and to have been accompanied by metallic compounds, sulphur, etc., also probably above their critical temperatures. Under these conditions—that is, a temperature of not less than + 365° C., and a pressure of not less than 200 atmospheres—water can only exist as a perfect gas. Minerals formed under such conditions are known as of pneumatolytic origin.

When the temperature sinks below this limit the water, if under sufficient pressure, remains an ordinary fluid, and the

deposits formed by it appear to undergo a change. To such conditions the deposits of ordinary fissure-veins should probably be attributed.

Finally, under conditions of high temperature and slight pressure very near the surface, water, as well as other compounds, may be converted into a vapor, and such deposits as may be formed by this action are said to be due to sublimation. Escaping gases from heated rocks near the surface in volcanic districts are called fumaroles. The name of fumaroles or fumarolic action is sometimes applied to contact-metamorphic deposits, but this usage appears to me to be incorrect.

Contact-metamorphic deposits occur in the United States, as well as in British Columbia and Mexico. Ordinarily, copper sulphides and magnetite are the principal ore-minerals, but they may carry a small quantity of gold. A certain small amount of gold has been derived from these deposits in the United States and British Columbia; just how much is very difficult to decide. In Mexico contact-metamorphic deposits are more common, and sometimes contain much gold. It is probable that more than $1,000,000 has been obtained from this source in Mexico; but here, again, exact figures are unobtainable.

Classification According to Age.

Introduction.—In stating the production of gold in the various States, it is necessary to adopt some unit for its measurement. The one selected is $1,000,000; this unit will be indicated by $M^2\$$.[5] In this manner the results will be much more clearly presented than by long series of figures. The most scientific way to express the product is doubtless in kilograms; but for the present purposes the adopted unit seems much more tangible and more easily understood.

From the Atlantic to the Pacific ocean, the mountains of North America contain gold, although the largest treasures are stored in the great ranges of the Cordilleran region. From the time of discovery up to 1900 the United States has produced about $M^2\$2{,}529$, Mexico at least $M^2\$200$, and possibly twice as much, and British North America $M^2\$140$, making a grand total of $M^2\$2{,}869$. This great product is divided among

[5] For example, $M^2\$1.0 = \$1{,}000{,}000$. $M^2\$2.25 = \$2{,}250{,}000$. $M^2\$0.5 = \$500{,}000$, etc.

primary veins of pre-Cambrian, Mesozoic, and Tertiary age. To separate the last two groups is in many cases a difficult matter.

Pre-Cambrian Deposits.—Gold was discovered in veins of the older rocks of the Appalachian Mountain region about 100 years ago, in Georgia, the Carolinas, Tennessee, Maryland, Virginia, and even farther north. Poorer deposits of the same kind have been found up to the Canadian line, and north of this richer gold-veins occur again in Quebec, Ontario, and Nova Scotia. Again, farther westward in the United States, in Michigan, probably pre-Cambrian gold-quartz veins occur on a smaller scale. Still farther west they are developed in the Black hills of South Dakota, and also in Wyoming. The last two are the only localities in the Cordilleran region in which pre-Cambrian deposits have been recognized.

The primary deposits in the above-mentioned districts are chiefly gold-quartz veins with free gold and auriferous sulphides. The veins were probably to a large extent formed before the Cambrian period, and are thus the most ancient deposits of the continent. Among the evidence pointing directly or indirectly to this conclusion, the following have especial weight: The Triassic sandstones of the Atlantic coast contain placer-gold; no important gold-deposits are found in the Palæozoic rocks of the Appalachian region; Carboniferous conglomerates in Nova Scotia are said to contain water-worn gold of older veins; in the Black hills the Cambrian conglomerates yield placers of the precious metal. During the 19th century the Southern States produced $M^2\$47.0$, Nova Scotia and adjacent provinces $M^2\$17.0$; during the last ten years the Southern States have yielded $M^2\$0.3$ and the eastern Canadian provinces from $M^2\$0.5$ to $M^2\$1.0$ per annum. The deposits are not rich according to our standards for the Cordilleran region, but the yield is steady, and can probably be relied upon for many years to come.

Economically, the most important pre-Cambrian deposits are found in the Black hills. The old pre-Cambrian schists here contain fissure-veins and seam-belts of free-milling gold-ores covered by Cambrian sandstones containing placer-gold. These deposits are worked on a large scale; they have yielded, since discovery in 1876, about $M^2\$74.0$, and produce annually $M^2\$3$ or $M^2\$4$.

Altogether, then, the pre-Cambrian deposits have given us, since discovery, $M^2\$138.0$. In most cases extensive erosion has taken place since these veins were formed, and the surface of the land at the time of their formation must in some cases, at least, have been thousands of feet above the level at which they are worked at present. They are the "roots" rather than the "tops" of veins.

Cretaceous Veins of the Pacific Coast.—The most important gold-belt in North America extends along the Pacific coast. It is throughout characterized by quartzose ores with free gold and auriferous sulphides. A great erosion has taken place since the veins were formed; and here, too, as in the pre-Cambrian deposits, we have to deal with the lower parts of veins, the upper parts having generally been removed, in many places to the extent of thousands of feet.

Beginning in Lower California, Mexico, 100 miles or more south of the boundary-line, this great belt continues through San Diego, Los Angeles, and Kern counties; through the central part of California, where it is developed in great strength; then on to northern California, southwestern and northeastern Oregon, and Idaho. In the latter States it is modified by the appearance of many silver-gold deposits and veins carrying auriferous sulphides without free gold. Covered for a distance by the lava-flows of the Cascades, it again appears in southern British Columbia—on Vancouver Island, among other places. Strong development is again attained in the Cariboo district, in central British Columbia, and it continues through the Omineca, Cassiar, and Atlin districts to the Klondike region. Thence, bending westward, it follows the Yukon to the western end of the continent at Nome, on the Seward Peninsula.

The Cretaceous age of this belt is clearly established in California. In Oregon and Idaho, a late Mesozoic age is extremely probable. In British Columbia and Alaska, the evidence is not so positive, and the deposits may possibly, in part, be older.

Throughout this immense stretch of country the veins are accompanied by a great development of placers. Placers are, indeed, characteristic of this class of gold-veins, and by far the larger part of the yellow metal has been obtained from them. At many places in California, as well as in Oregon and Alaska, the veins from which these placers were derived have been very

disappointing, the fact being that the primary deposits are often scattered in many little seams rather than concentrated in great veins.

California alone has yielded M²$1,380.0 from this belt; Oregon M²$54.0; British Columbia and Northwest Territory M²$123.0; Alaska M²$30.0. The total is over M²$1,700.0. During 1900 the belt probably yielded M²$54.0, of which one-half came from British Columbia and the Yukon. This represents a great increase compared with the figures of ten years ago, and it is doubtful whether this increase will be maintained. At least M²$27.0 was obtained from the placers on the Yukon and in Alaska. If no further great discoveries are made in this region, our knowledge of placers forces us to the belief that this last figure will gradually decrease. Quartz-mining will to some degree compensate for this; but the quartz-mines have usually, in the older districts, yielded less than the corresponding placers. California's output will doubtless be maintained at about the present figure for many years.

Late Cretaceous or Early Tertiary Deposits (Central Belt).—Besides the Pacific gold-belt, there is a broad zone in the central and eastern part of the Cordilleran region which contains an abundance of gold-deposits of varying character. Many of these seem to have been formed a little later than the California gold-quartz veins, perhaps largely at the very close of the Cretaceous, or possibly at the very beginning of the Tertiary period.

This broad zone begins in Mexico, where the Pacific States of Sonora and Sinaloa contain many gold-veins in pre-Cretaceous sediments, granites, and crystalline schists. According to Professor Dumble, many of the Sonoran deposits occur in Triassic rocks, and are considered by him to be of the same age as the California veins. Similar veins in old rocks continue through the southwestern part of Arizona, but their age is not definitely known. Many of them are important producers.

Although undoubted Tertiary deposits prevail in Nevada, those of an older period are probably not absent. A few of them are free-milling gold-quartz veins, but in the majority the ores consist chiefly of sulphides alone, and the value of the silver exceeds that of the gold.

In Utah the principal gold-mines are those of the Mercur district, in which ores suited to the cyanide process occur in limestone close to intrusive sheets of porphyry. These yielded over M²$2.0 in 1900. Most of the remaining amount credited to Utah is derived from gold-bearing silver-ores of the smelting class, which are found in veins and irregular deposits in sedimentary rocks close to bodies of intrusive (Cretaceous?) porphyries. The future of the gold-production is here very closely connected with the vicissitudes of the silver- and copper-markets.

In Colorado the most important Cretaceous gold-deposits are those of Leadville. Here, again, the ores occur in Palæozoic sediments and porphyry; and the gold-production, small until a few years ago, reached M²$2.7 in 1900.

In Idaho and Montana late Mesozoic and early Tertiary veins are developed on a large scale. We note here the interesting fact of a junction with the Pacific belt, through northeastern Oregon and central Idaho, into Montana. Going eastward, the free-milling and quartzose character is partly maintained, but silver becomes more prominent in the ores, and auriferous sulphide ores often replace the native gold. Central Idaho formerly contained many rich placer-camps, which have yielded their millions. As in Oregon and in Montana, the first years of mining were largely devoted to working this form of deposit. Bannack, Alder Gulch, Helena, and Confederate Gulch are well-known names of celebrated placer-camps in Montana. The great producing quartz-mines are not, however, those from which the placers have been derived. They contain much silver, and pan-amalgamation is the most common process.

After the exhaustion of the placers, silver-ores of the smelting class, containing galena and other sulphides, together with a little gold, were also extensively mined. This industry has declined during recent years; but, as a partial compensation, at least M²$1.0 per annum is obtained as a by-product from the smelting of the copper-ores of Butte.

The majority of gold-bearing veins in Idaho and Montana are genetically connected with the intrusion of very large bodies of granitic rocks during the Cretaceous period. This explains the fact of relationship with the Pacific gold-belt, for there, too, the veins stand in undoubted causal connection with the great Mesozoic granitic "batholiths," as the large intrusive

bodies are called. As far as we know, these batholiths are either absent or only developed on a small scale in Nevada, Utah, and Arizona.

In the southern part of British Columbia are a number of veins which contain copper-gold ores, and to less extent milling-ores, and which are believed to belong to the late Mesozoic period. They are chiefly found in diorites and allied intrusive rocks.

Looking at this central Mesozoic gold-belt as a whole, it is believed that, north of Mexico, it has produced at least M²$286.0 since discovery, and during 1900 its tribute to the total of North America was about M²$14.0.

In this chain of deposits the gold-production is closely associated with the silver and copper industry, for sulphide ores prevail over those containing native gold. No wonderful increase of production may be expected, but rather a steady maintenance, and possibly a gradual growth if there is no serious decline in the values of copper and silver. Placer-mining, with its dwindling tendency, is still represented in Montana and Idaho; in the other States of this belt it plays a comparatively insignificant part.

Tertiary Deposits.—A fourth and last class of gold-producing veins are of Tertiary, mostly post-Miocene, age. They are usually found in regions of intense volcanic activity cutting across heavy andesite-flows, more rarely rhyolite and basalt. In many cases these veins may be seen to continue down into the underlying floor, upon which the volcanic flows were poured out, and which may be of igneous or sedimentary character. Sometimes, indeed, an active erosion has removed much of the volcanic flows, and the veins crop directly in older rocks.

The majority of these veins in Tertiary lavas have certain common and persistent characteristics and form a fairly well-defined class, usually called *propylitic veins*, alluding to the peculiar alteration of adjoining rocks which seems to characterize them. The ores are nearly always quartzose, and sometimes contain silver alone; more rarely gold alone; but most commonly both gold and silver in about equal quantities by value.

They are often characterized by great richness, the word "bonanza" being employed to represent their big ore-shoots.

While some of these veins yield steady and reliable products, many of them burst out in sudden blazes of glory like shooting-stars, only to be extinguished with equal suddenness. The gold is nearly always in such peculiarly fine distribution that extensive and rich placers are rarely formed from them; contrasting, in this respect, with conditions in the Pacific gold-belt. Many of them, in districts of great erosion, show that the values continue in depth; but the ore is perhaps less rich than in those parts formed nearer to the original surface. In this class we evidently have to do with the part of the vein which was not far from the original surface at the time of ore-deposition. In some cases the ores can be proved to have been formed but a few hundred feet from this surface. Instead of roots of veins, as in the Pacific and Appalachian belts, the propylitic veins ordinarily represent the uppermost part of the area of deposition along the fissure. Not all of the distinctly Tertiary veins possess, however, the character of typical propylitic veins. Many deviate considerably, but few, if any, show the typical development of gold-quartz veins of the Pacific coast.

This belt of Tertiary veins is most extensively developed in Mexico. The central plateau contains the great silver-veins of this class, which always contain a small amount of gold, and from which the greater part of Mexico's gold-output has been derived. But along the western slope of the Sierra Madre in Chihuahua, Zacatecas, and Sinaloa, heavy andesite-flows contain gold-silver veins of great importance, and are, together with the veins of the older belt in Sonora, largely responsible for the greatly-increased gold-production of Mexico.

Entering the United States, Tertiary veins are found in Arizona and New Mexico. In Arizona, probably both Cretaceous and Tertiary veins occur, and in the present state of our knowl edge their separation is sometimes difficult. The Commonwealth mine, in Cochise county, is a prominent representative of the younger veins; it breaks through rhyolite, and is at present one of the largest producers of the Territory. One-third of the value is in gold, and the rest in silver.

In New Mexico are several districts containing these veins—chiefly, it is said, in andesitic rock; but the output of this Territory has not as yet reached the million-dollar mark.

The development of Tertiary veins continues northward into

Nevada and California. San Bernardino county, in California, contains silver-deposits in rhyolite, and probably also Tertiary gold-veins. Veins of similar kind continue along the eastern foot of the Sierra Nevada as far north as Alpine county, and become most productive in Mono county; the mines at Bodie, in andesite, produced in nine years M²$12.0 in gold, besides much silver.

Northward from this point few Tertiary veins are found, though intense volcanic activity prevailed in the northern Sierra Nevada and the Cascades during the Tertiary. At one or two places in Oregon, chiefly in the Bohemia district in the Cascade mountains, the volcanic rocks contain gold-veins, but they have not as yet yielded much. Continuing northward into Washington, the Monte Cristo veins, in andesite and diorite, represent this type, but are not credited with extraordinary production.

No veins of this class are thus far known in British Columbia or the Northwest Territory, but on the southern coast of Alaska we meet sporadic cases again. The Apollo mine, on Unga Island, breaks through andesite, and has produced gold for the last few years to a maximum annual amount of about $400,000. The Alaskan peninsula also shows evidence of more recent Tertiary mineralization.

Returning southward to Nevada, this class of gold-deposits is abundantly represented. The Comstock vein, Tuscarora, Eureka, Tonopah, the De Lamar veins, are known or believed to be of propylitic character, and, with the exception of the latter, occur in volcanic rocks. The Comstock easily leads, with an estimated production of over M²$148.0 in gold, and the other districts have contributed heavily to the total output, although all also contain much silver in their ores. The production of Nevada has fluctuated greatly, and after long decline is again increasing.

A line of Tertiary veins continues northward from Nevada into Idaho. In the southern part of that State they are represented by the Owyhee gold-silver mines, which since their discovery have yielded M²$12.0 in gold; and farther north by the bonanzas of Rocky Bar, Atlanta, and Custer, which, probably, should be referred to this type. Still farther north is the Thunder Mountain district, which, if reports are reliable, con-

tains gold in rhyolite. No Tertiary primary gold-deposits have been reported north of this point.

Veins of this class occur in Utah—for instance, at the Horn-Silver mine and at Tintic; but these deposits carry very little gold.

Returning now to New Mexico, a belt of these veins continues northward into Colorado and reaches a development not known elsewhere, except in Mexico. The total output of Colorado is probably about M²$250.0. In 1900 the output was M²$28.8. Excepting the Leadville deposits, the principal gold-producing districts are of Tertiary age. Oldest among them as to discovery are the veins of Gilpin, Boulder, and Clear Creek counties, which crop in Archæan rocks and are accompanied by andesite dikes. These districts have been remarkably steady producers since 1859, and contribute annually about M²$3.0. They promise to continue their production for a long time. Another important locality is the San Juan district, in southwestern Colorado, where strong quartz veins cut heavy andesitic flows. The yield has increased greatly since 1890, and in 1900 reached M²$4. It promises well for the future; and some of the mines, like the Camp Bird, have proved veritable bonanzas. The output will probably continue to increase for some years. An interesting feature of the San Juan region is that in some districts which have suffered great erosion the veins are found to continue into bodies of intrusive diorites and porphyries of later age than the andesites, thus offering a comparison of conditions near the original surface and at a considerable distance below it.

Finally, there is the great Cripple Creek district, which has yielded M²$77.3 during the period 1892 to 1900 inclusive, and in 1900 produced M²$18. A network of veins occur in andesite, phonolite, and underlying granite, and have thus far chiefly carried telluride ores. What may be expected of this district in the future is a most important question, and one not easy to answer.

North of Colorado the propylitic deposits are almost absent, though they appear in sporadic form in Montana.

Roughly calculated, about M²$564.0 has been contributed by the propylitic veins to the total gold-output of the United States, to which should probably be added at least M²$160.0 from Mexico. For 1900 we may estimate M²$36.0 as the output of these veins in the United States, and perhaps M²$7.0 in Mexico.

Conclusions.

Summing up the data obtained, we should estimate as follows:

Source of Production of Gold in North America.

	Total M$.	1900 M$.
Pre-Cambrian,	139.0	5.0
Cretaceous (Pacific),	1,719.0	54.0
Cretaceous and early Tertiary (Central),	287.0	14.0
Tertiary (largely propylitic),	724.0	43.0
	2,869.0	116.0

The great increase in the gold-production of the continent during the last ten years has been due, *first*, to important discoveries of new districts in almost every producing State; *second*, to the increased activity in many old gold-districts and mines; *third*, to the late great development of copper-smelting, by which much gold has been obtained as a by-product; *fourth*, to the introduction of the cyanide process, rendering many classes of low-grade ores and tailings available; and, *fifth*, to the introduction of hydraulic elevators and dredgers, giving a new lease of life to many old and decaying placer-camps.

Many considerations suggest that the increase will probably not continue in the same ratio for the next few years, providing that no great discoveries are made of new placers in the far north or of vein-systems like that of Cripple Creek. The greater part of the increase has been derived from the Northern placers and from Cripple Creek; in 1900 the gold derived from these sources amounted to M$46.0. Subtract this from a total for North America of M$116.0, and only M$70.0 remains. The placer-fields now known in Alaska and Northwest Territory will in all probability gradually decrease their output during the next few years. Many reserves of old mill-tailings and dredging-grounds to which new processes have been applied are being rapidly exhausted. Some districts producing gold from copper-ores and others working bonanzas of the Tertiary veins will not improbably lessen their output. Against this stand always the possibility of new discoveries and the introduction of improved processes. Tentatively striking a balance, a small decrease of the gold-production of North America would seem more likely, for the next few years, than an increase.

TABLE I.—*Gold-Production of North America.*

Unit: M²$ = $1,000,000.

Divisions. United States.	Total from Discovery to 1900, incl. M²$.	1877–1900, incl. M²$.	M²$. 1900.	1901.	1902.[a]
Alaska	30.7	30.7	8.2	6.9	7.8
Arizona	42.1	33.6	4.2	4.1	4.2
California	1,380.0(?)	351.1	15.8	16.9	17.1
Colorado	251.1(?)	204.3	28.8	27.7	27.5
Idaho	112.8	42.8	1.7	1.9	2.1
Montana	203.5(?)	83.6	4.7	4.7	4.1
Nevada	250.0(?)	99.7	2.0	3.0	3.5
New Mexico	17.6	13.3	0.8	0.7	0.7
Oregon	54.5	29.7	1.7	1.8	1.9
South Dakota	90.0	89.4	6.2	6.5	7.4
Utah	27.0	24.1	4.0	3.7	3.7
Washington	21.4(?)	8.9	0.7	0.6	0.4
Wyoming	1.0(?)	1.0	0.1		
Appalachian States (Mainly Georgia and the Carolinas.)	47.0	8.0	0.3	0.2	0.3
	2,528.7	1,020.2	79.2	78.7	80.7
British North America.					
Nova Scotia	13.7	9.7	0.6	0.5	
Quebec	2.0(?)	0.2			
Ontario	1.2(?)	1.1	0.3	0.2	
British Columbia	70.7	21.1	4.7	5.3	
N. W. Territory	52.6	52.6	22.3	18.0	14.6
	140.2	84.7	27.9	24.0	
Mexico	200.0(?)	66.5	9.0	10.3	
Total	2,868.9	1,171.4	116.1	113.0	

[a] Preliminary estimate by the Director of the Mint.

NOTE TO TABLE I.—This table has been compiled chiefly from the Mint Reports of the United States. Regarding the United States, accurate statistics date from 1877; the first column, showing the total production of each State, is to a great extent based on estimates of the output of early placer-mining, by J. Ross Browne, R. W. Raymond, and the Mint Bureau. The figures given for California, Nevada, Montana, Washington, Oregon, and Colorado are especially uncertain. The total (M²$2,528.7) exceeds the estimate of the Mint Bureau by nearly M²$150.0, though the two calculations are probably based on the same evidence. If the results of the Mint Bureau are accepted as correct, the figures given in the first column are too high; but how and where the correction should be applied is very difficult to say. In most States, however, the figures in the first column will be considered too low, locally-current estimates being much higher.

The figures for British North America are probably fairly correct, but those from Mexico are admittedly only estimates by the Mint Bureau or by other statisticians.

TABLE II.—*Tentative Distribution of Gold-Production of North America According to Age of Primary Deposits.*

Unit: $M^2\$ = \$1{,}000{,}000$.

Divisions. United States.	Distribution of Total Production. From Discovery to 1900, inclusive. $M^2\$$.				Distribution of Production of 1900. $M^2\$$.			
	Pre-Cambrian.	Mesozoic (Pacific Coast Belt).	Late Cretaceous or Early Tertiary (Central Belt).	Tertiary (Mostly Post-Miocene).	Pre-Cambrian.	Mesozoic (Pacific Coast Belt).	Late Cretaceous or Early Tertiary (Central Belt).	Tertiary (Mostly Post-Miocene).
Alaska	.....	29.7	.....	1.0	.....	7.8	.....	0.4
Arizona	.....	22.1	.....	20.0	.....	.....	2.0	2.2
California	.....	1,350.0	.....	30.0	.....	14.8	.....	1.0
Colorado	.....	.....	34.0	217.1	.....	.....	2.7	26.1
Idaho	.....	90.0	.....	22.8	.....	0.7	.....	1.0
Montana	.....	.....	200.0 ?	3.5 ?	.....	.....	4.7	
Nevada	.....	.....	20.0	230.0	.....	.....	?	2.0
New Mexico	.....	.....	7.6 ?	10.0 ?	.....	.....	0.4	0.4
Oregon	.....	54.0	.....	0.5 ?	.....	1.7		
South Dakota	74.0	.....	.....	16.0	3.8	.....	.....	2.4
Utah	.....	.....	25.0	2.0 ?	.....	.....	4.0	?
Washington	.....	10.0	.....	11.4	.....	0.2	.....	0.5
Wyoming	1.0	.....	.....	.....	0.1			
Appalachian States (Mainly Georgia and the Carolinas.)	47.0	.....	.....	.....	0.3			
	122.0	1,555.8	286.6	564.3	4.2	25.2	13.8	36.0
British N. America								
Nova Scotia	13.7	.....	.....	.....	0.6			
Quebec	2.0?							
Ontario	1.2?	.....	.....	.....	0.3			
British Columbia	.....	70.7	.....	.....	.....	4.7		
N. W. Territory	.....	52.6	.....	.....	.....	22.3		
	16.9	123.3	.....	.....	0.9	27.0		
Mexico	.....	40.0?	.....	160.0?	.....	2.0?	.....	7.0?
Total	138.9	1,719.1	286.6	724.3	5.1	54.2	13.8	43.0

NOTE TO TABLE II.—It should be expressly stated that this table is only a first tentative estimate, as in very many cases the data for exact subdivision are not available. The distribution for 1900 is, of course, probably more nearly correct than the segregation of the total product attempted in the first part of the table.

Discussion.

(*Trans.*, xxxiii., 1077.)

Willet G. Miller, Toronto, Canada: With regard to Mr. Lindgren's impression that the gold-supply of the world will gradually decrease if no further important improvements are made in the processes of gold-extraction, it seems to me that no very important improvements are needed to keep up the present production for many years to come. In many regions there are large deposits of auriferous material which can be worked if present conditions are slightly changed. In the territory occupied by the Archæan protaxis of the Province of Ontario, for instance, there are gold-deposits of large size which apparently could be worked at a profit if the cost of production were slightly decreased. Many of these deposits average approximately from $1 to $1.50 per ton, and consist of quartz veins, shattered, impregnated masses of granite and other rocks, and placer-deposits.

In the Rainy River district, in Western Ontario, gold occurs in a mass of rock which is thus described in the government reports of the Province: "It consists of a mixture of altered granite, quartz, and chlorite, with streaks of green schist. It has been traced 3 or 4 miles, and has a general direction of northeast and southwest. The boundaries are rather indefinite, but as near as can be ascertained it is 462 ft. wide at the widest known place. On the location we are dealing with it varies in width from 100 to 200 ft. One hundred feet is its width at the narrowest place, as far as known."[6] Judging from careful tests which have been made, much of this rock-matter contains $1.50 value per ton in free-milling gold. It has not been found possible, however, to work it at a profit.

Gold has been found in the Vermilion River placers, north of Sudbury, in a territory covering many square miles.[7] The metal occurs free, usually in a state of very fine division, and inclosed in pebbles of quartz. Fire-assays show that the sand and gravel frequently carry a value of more than $2 per ton. Much of the material, while lower in value, averages from 12 to 15 cents per cubic yard. While the existence of these placers

[6] *Seventh Report of the Ontario Bureau of Mines*, pp. 65, 130 and 131 (1897).

[7] *Idem*, pp. 256 to 259; *Tenth Report*, pp. 151 to 159 (1901).

has been known for some years, success has not been achieved in treating them. It would seem, however, that a comparatively slight improvement in the present methods of treatment should bring about the profitable working of them.

A year or two ago similar placers were discovered on Savant lake, which is about 150 miles northwest of Port Arthur and 500 miles from the last-mentioned area. In panning these sands and gravel I obtained a very few colors. Fire-assays, however, show that much of the material, which consists of coarse sand, gravel, and boulders, averages about $1 per ton in gold.[8] Some of the metal contained in the fragments of rock probably could not be extracted by free-milling processes. Similar deposits, which have not been examined as to their gold-content, cover a large territory in this little-explored region, and it would appear that the metal is present in most of this gravel.[9] In the vicinity of Savant lake the thickness of the sand- and gravel-deposits is at some points over 100 ft. The deposits are of glacial origin, and the average of the gold-content of the gravel from the tops of the higher hills is similar to that found at lower levels.

The rocks over a great part of the Archæan area of Canada are similar in character, and there is reason to believe that gold-deposits carrying values like those mentioned occur widely extended over this vast, imperfectly-explored region. It may be many years, probably not till the production of the richer deposits of other parts of the world begins to decline, before these deposits are worked. Since the gold-values which they carry, however, are so close to those of deposits which even now are being profitably worked, it is within the range of probability that the Canadian protaxis will, in the years to come, be the scene of a great gold industry. Low-grade deposits in other parts of the world also will then add their quota, and the day of a great decline in gold-production, a time of "not only physical devastation, but moral and political decay," thus seems far distant.

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[8] *Twelfth Report of the Ontario Bureau of Mines* pp. 89, 90 (1903).

[9] *Summary Report of the Geological Survey of Canada*, pp. 92 to 93 (1901).

W. L. AUSTIN, New York, N. Y.: In Mr. Lindgren's instructive paper the statement is made in the reference to the pre-Cambrian gold-quartz veins of South Dakota and Wyoming, that these two "are the only localities in the Cordilleran region in which pre-Cambrian deposits have been recognized." Further along in the paper [Part III., not reprinted here] it is stated that "gold-deposits of Archæan age are not known in Colorado. As far as the age has been determined, the deposits are divided into a smaller Mesozoic and a much greater Tertiary and probably chiefly post-Miocene group."

Mr. Lindgren has apparently overlooked an extensive auriferous deposit described by Messrs. E. C. and P. H. van Diest in a paper read before the Colorado Scientific Society in 1894. As the article referred to is not readily accessible, and as the said deposit is of considerable extent—the beds cropping out 3 miles in one direction, and 1 mile in another—a few extracts from the van Diest paper may be considered pertinent in discussing "The Geological Features of the Gold-Production of North America." Furthermore, this matter has commercial importance, for these beds may become at an early day a not-inconsiderable source of the precious metal.

The van Diests refer to this deposit as Cambrian; but it is thought that no serious attempt has been yet made to fix the age other than approximately. It is apparently lower than the Silurian, and in some respects resembles the pre-Cambrian deposits of the Black hills.

Quoting from the van Diest paper: "The district examined is on the Rito Seco. This little stream unites with the Rio de la Culebra near San Luis—the county seat of Costilla county—a region nearly in the center of the lower neck of the Pliocene lakes, named by Endlich the Coronados lakes. Leaving San Luis, the Rito flows for about 6 miles in a northerly direction through scattered *débris*, when the lake beds forming the foot hills are reached. Here the road takes an easterly direction, winding its way for about 3 miles through a wide and shallow canyon which has been eroded from the lake beds. According to Hayden the lake beds at this point should lie against the Upper Carboniferous. No dark-red sandstones, such as were observed in coming over Veta Pass, could be seen anywhere, but we found instead, on the north side of the Rito for a dis-

tance of a quarter of a mile, some quartzite beds forming steep cliffs, while further along the stream flows over light-colored limestones and finally over granite.

"Directly north of the creek a thin bed of conglomerate appears. It is composed of light-bluish and greenish quartz pebbles cemented by oxides of iron and manganese. Resting on this bed follow layers of quartzites whose total thickness is estimated at 160 ft. These quartzites are saccharoidal in appearance, of pure white color when freshly broken, but stained by a film of iron oxide where they have been exposed to the influence of the weather. The quartzites are succeeded by a thin bed of argillaceous shale, and the whole section is topped by layers of light-grey siliceous limestones for about 200 ft., where a quartzy parting separates them from others of somewhat darker color. . . . Although no fossils have been found as yet in the described beds, it is clear from a stratigraphic point of view that the limestones are of Silurian and the quartzites of Cambrian age.[10] An igneous dike about 30 ft. in width runs through the limestone beds in a northerly and southerly direction. It is of a dark purplish-brown color, very compact and fine grained. In appearance it resembles more the older basalt occurring between the lake beds, and is distinctly different from the younger basaltic overflow which caps the beds south and west of the Rito Seco. The dike had had no disturbing influence whatever on the limestone beds, as is shown by the cuts run into the limestone on either side of the dike. Northerly and higher up on the mountain a light-colored porphyry was observed, but owing to lack of time there was no opportunity afforded to determine what the extent of this eruptive mass might be, and what connection, if any, it might have with the dike, nor could we determine if, in an easterly direction, other quartzites and limestones rest on the granite. . . .

"Close inspection of the rusty faces of the quartzite cliff has lately revealed that three distinct layers of auriferous iron pyrite occur between the quartzite beds, the lower one measuring about 12 ft. in thickness, the next about 14 ft., and the upper one 8 ft. At the time of our visit a drift had been run

[10] As Cambrian conglomerates bear witness to pre-Cambrian gold-veins, then these deposits must be pre-Cambrian in the same sense as those of the Black hills.

in the middle seam for a distance of 40 ft. The breast and sides of this drift stood in almost solid pyrite. This pyritic ore as broken down assays from $5 to $15 in gold per ton. So far no copper-, zinc-, or other sulphides have been observed with the deposit. The field, although but little employed, seems to be of promise, and it is to be hoped that development work will be uninterruptedly prosecuted."[11]

Since the above was written these quartzite-beds have been exploited somewhat further; and it is now thought that the beds are more nearly an arkose than quartzite. This deposit is so little known that it is not surprising it should have escaped Mr. Lindgren's notice.

[11] *Proceedings of the Colorado Scientific Society*, vol. v., pp. 76 to 80.

No. 17.

Osmosis as a Factor in Ore-Formation.

BY HALBERT POWERS GILLETTE, NEW YORK, N. Y.

(New York Meeting, October, 1903. *Trans.*, xxxiv., 710.)

FROM the known laws of physical chemistry I believe it can be shown that progressive mass movement of water solutions in channels has seldom been the means of ore-concentration in veins. It is my purpose in this paper to show that the force known as "osmosis" has been the principal factor in ore-formation. Convection-currents have doubtless supplemented osmosis, and the two working together have been the agencies that have gathered the scattered particles of rare minerals into the larger masses which are called ore.

Osmosis is commonly thought of as a vague, feeble force that causes slow diffusion of dissolving matter through the solvent. That it is a measurable force, often of great intensity, few know, except those who are familiar with the laws of modern physical chemistry. Therefore, I may be pardoned for going briefly into the elementary mathematics of osmotic pressure and of convection-currents.

The velocity of water moving through any channel is given by the Chézy formula:

(1) $v = c\sqrt{rs}$, in which r is the hydraulic mean radius; s, the slope of the channel in which gravity is the sole propulsive force; and c, the coefficient of roughness of the sides of the channel.

From this formula it is evident that the smaller the channel, the smaller the velocity of water under a constant head. In rock-crevices, therefore, where the head is constant, water moves much more slowly than in large fissures, and in moving through sand or porous rock it is to an even greater degree retarded. Hence, if a mass of water-saturated sand be heated, the finer the sand-grains, the more slowly will the temperature rise at parts remote from the source of heat. Conversely, cooling is retarded the smaller the interstices or channels through which the convection-currents move. The importance of this

fact will appear later. Osmosis is the force which drives a solute through a solution. When a substance dissolves it behaves in many respects exactly as if it were vaporized. In fact, it has been proved by Van't Hoff that "The osmotic pressure of a substance in solution is the same pressure which that substance would exert were it in gaseous form at the same temperature and occupying the same volume."[1]

Expressed mathematically the law is:

$$(2)\quad p = \frac{RT}{V}$$

in which, p = osmotic pressure in pounds per square inch.
R = the gas constant = 1,206 lb. per sq. in.
T = absolute temperature = t° (Centigrade) + 273.
V = volume of the solvent containing one molecular weight of the solute.

$$(3)\quad V = \frac{100\,M}{r}$$

in which, M = sum of the atomic weights of the atoms in a molecule of the substance.
r = the rate per cent. of the solution.

Hence:

$$(4)\quad p = \frac{1{,}206\,r\,(t° + 273)}{100\,M} = \frac{12\,r\,(t° + 273)}{M}.$$

I have deduced equation (4) for convenience in ascertaining and comparing osmotic pressures. Thus, sugar is $C_{11}H_{22}O_{11}$. Hence for sugar, $M = (12 \times 11) + (1 \times 22) + (16 \times 11) = 342$. For a 2-per-cent. sugar solution, $r = 2$. Therefore at 15° C. we have the osmotic pressure according to equation (4) as follows:

$$p = \frac{12 \times 2\,(15 + 273)}{342} = 20.2 \text{ lb. per sq. in.}$$

By actual experiment p was found to be 20 lb. per sq. in. under these conditions; and Van't Hoff's law of osmotic pressure has been repeatedly proved by similar tests. From the above statement it is clear that osmosis is far from being a vague or feeble force.

When due to a rise in temperature, or for other reasons, ground-water at any given point begins to dissolve a mineral,

[1] *Elements of Physical Chemistry*, by J. Livingston R. Morgan, New York, John Wiley & Son, p. 96.

that mineral is immediately forced by osmotic pressure out to the extreme confines of the vessel holding the water. Let us suppose, therefore, that a dike-intrusion has so heated the surrounding waters that they have taken up a burden of PbS; evidently, then, osmosis will force this PbS throughout the mass of water into every cranny, crevice, fissure, or cavity. It requires no convection-currents to accomplish this distribution, although convection will hasten the process. Having taken up its full burden of PbS there comes a period of inactivity, until the temperature begins to fall. This fall of temperature will be most rapid near the surface of the earth and it will be most rapid in the larger water channels, for the reason that circulation there is least retarded.

In the case of dike-intrusion, I believe that the shrinking of the dike-matter will open the largest crevices and channels along the dike itself, and I conceive that surface-waters flowing into these shrinkage-cracks will accelerate the cooling near the dike. Hence, in such cases, contact ore-deposits will be found on one side of a dike, and that side will be the side which originally faced uphill. The down-flowing surface- or ground-water will enter the first crevices it meets and hasten the cooling there, and it is quite evident that where cooling is fastest, crystallization of dissolved mineral will first begin. Let the smallest speck of galena be crystallized out, and immediately osmosis will force more dissolved galena to that point, and thus feed the crystal-mass. Heretofore, the deposition of ore nearest the once-molten dikes has been inexplicable, but in no other place could it have started, and, once started, the tendency toward crystal growth must be due entirely to osmotic pressure

Let us consider for a moment certain other conditions that accelerate cooling, since it is now evident that much depends upon the first cooling of the solution. At the intersection of two fissures the cooling should be most rapid, for at that point two channels supply convection-currents. Hence the deposition of the most insoluble minerals should occur first at vein-intersections, a circumstance which is often verified in known ore-deposits. Again, in fissure walls that have been striated by slipping past one another, the grooves form channels in which convection-currents move most rapidly, and, as should be ex pected, the most insoluble minerals are found in the grooves.

This, I believe, explains "Clayton's law."[2] Since the richest minerals are ordinarily the most insoluble, I offer this general proposition: "Bonanzas should be sought at points where circulation has been freest, namely, in the widest and most open channels."

Since the relative solubility of minerals has evidently played so important a rôle in ore-formation, a few suggestions may not be out of place. Hot waters carrying metallic sulphides in solution must carry also a great burden of alkaline salts. In fact, the solubility of the metallic sulphides is due to the presence of these alkaline salts which form new ions with the sulphides, just as potassium cyanide dissolves gold salts by forming new ions with the gold. One well-known geologist has erred in assuming that the "solubility product" of every mineral is increased by the presence of other minerals in solution. This, in passing, I would say is not so; for it is only when new ions are formed with the added elements, that solubility is effected, and there are many minerals which do not combine to produce these new ions. The metallic sulphides and the ions formed by them have a very low "solubility product" at best, and when a lowering of temperature causes the sulphides to crystallize out, the "solubility products" of the substances in solution are often so increased that more country-rock is dissolved. In this manner for every particle of sulphide deposited by crystallization, a particle of country-rock may be dissolved. This, I take it, is the true explanation of the so-called "metasomatic replacement" which has been regarded as a true chemical reaction, or precipitation. I have never been able to believe that galena and other natural metallic sulphides are chemical precipitates, and one of my strongest reasons for this disbelief has been the fact that chemical precipitates of lead and similar sulphides are flocculent and never crystalline. How cubical galena could be precipitated chemically from solution, by any reducing agent in nature, has ever been a most serious stumbling block. I am convinced now that practically all of the hypothetical equations written by geologists to account for ore-deposition by chemical reaction are erroneous. Many of these equations can be demonstrated to be false from the laws of thermal chemistry, and few of

[2] *Ore-Deposits of the United States and Canada*, J. F. Kemp, p. 49.

Conclusions.

Summing up the data obtained, we should estimate as follows:

Source of Production of Gold in North America.

	Total M²$.	1900 M²$.
Pre-Cambrian,	139.0	5.0
Cretaceous (Pacific),	1,719.0	54.0
Cretaceous and early Tertiary (Central),	287.0	14.0
Tertiary (largely propylitic),	724.0	43.0
	2,869.0	116.0

The great increase in the gold-production of the continent during the last ten years has been due, *first*, to important discoveries of new districts in almost every producing State; *second*, to the increased activity in many old gold-districts and mines; *third*, to the late great development of copper-smelting, by which much gold has been obtained as a by-product; *fourth*, to the introduction of the cyanide process, rendering many classes of low-grade ores and tailings available; and, *fifth*, to the introduction of hydraulic elevators and dredgers, giving a new lease of life to many old and decaying placer-camps.

Many considerations suggest that the increase will probably not continue in the same ratio for the next few years, providing that no great discoveries are made of new placers in the far north or of vein-systems like that of Cripple Creek. The greater part of the increase has been derived from the Northern placers and from Cripple Creek; in 1900 the gold derived from these sources amounted to M²$46.0. Subtract this from a total for North America of M²$116.0, and only M²$70.0 remains. The placer-fields now known in Alaska and Northwest Territory will in all probability gradually decrease their output during the next few years. Many reserves of old mill-tailings and dredging-grounds to which new processes have been applied are being rapidly exhausted. Some districts producing gold from copper-ores and others working bonanzas of the Tertiary veins will not improbably lessen their output. Against this stand always the possibility of new discoveries and the introduction of improved processes. Tentatively striking a balance, a small decrease of the gold-production of North America would seem more likely, for the next few years, than an increase.

TABLE I.—*Gold-Production of North America.*

Unit: M²$ = $1,000,000.

Divisions. United States.	Total from Discovery to 1900, incl. M²$.	1877–1900, incl. M²$.	M²$. 1900.	1901.	1902.[a]
Alaska	30.7	30.7	8.2	6.9	7.8
Arizona	42.1	33.6	4.2	4.1	4.2
California	1,380.0(?)	351.1	15.8	16.9	17.1
Colorado	251.1(?)	204.3	28.8	27.7	27.5
Idaho	112.8	42.8	1.7	1.9	2.1
Montana	203.5(?)	83.6	4.7	4.7	4.1
Nevada	250.0(?)	99.7	2.0	3.0	3.5
New Mexico	17.6	13.3	0.8	0.7	0.7
Oregon	54.5	29.7	1.7	1.8	1.9
South Dakota	90.0	89.4	6.2	6.5	7.4
Utah	27.0	24.1	4.0	3.7	3.7
Washington	21.4(?)	8.9	0.7	0.6	0.4
Wyoming	1.0(?)	1.0	0.1		
Appalachian States (Mainly Georgia and the Carolinas.)	47.0	8.0	0.3	0.2	0.3
	2,528.7	1,020.2	79.2	78.7	80.7
British North America.					
Nova Scotia	13.7	9.7	0.6	0.5	
Quebec	2.0(?)	0.2			
Ontario	1.2(?)	1.1	0.3	0.2	
British Columbia	70.7	21.1	4.7	5.3	
N. W. Territory	52.6	52.6	22.3	18.0	14.6
	140.2	84.7	27.9	24.0	
Mexico	200.0(?)	66.5	9.0	10.3	
Total	2,868.9	1,171.4	116.1	113.0	

[a] Preliminary estimate by the Director of the Mint.

NOTE TO TABLE I.—This table has been compiled chiefly from the Mint Reports of the United States. Regarding the United States, accurate statistics date from 1877; the first column, showing the total production of each State, is to a great extent based on estimates of the output of early placer-mining, by J. Ross Browne, R. W. Raymond, and the Mint Bureau. The figures given for California, Nevada, Montana, Washington, Oregon, and Colorado are especially uncertain. The total (M²$2,528.7) exceeds the estimate of the Mint Bureau by nearly M²$150.0, though the two calculations are probably based on the same evidence. If the results of the Mint Bureau are accepted as correct, the figures given in the first column are too high; but how and where the correction should be applied is very difficult to say. In most States, however, the figures in the first column will be considered too low, locally-current estimates being much higher.

The figures for British North America are probably fairly correct, but those from Mexico are admittedly only estimates by the Mint Bureau or by other statisticians.

TABLE II.—*Tentative Distribution of Gold-Production of North America According to Age of Primary Deposits.*

Unit: M²$ = $1,000,000.

Divisions. United States.	Distribution of Total Production. From Discovery to 1900, inclusive. M²$.				Distribution of Production of 1900. M²$.			
	Pre-Cambrian.	Mesozoic (Pacific Coast Belt).	Late Cretaceous or Early Tertiary (Central Belt).	Tertiary (Mostly Post-Miocene).	Pre-Cambrian.	Mesozoic (Pacific Coast Belt).	Late Cretaceous or Early Tertiary (Central Belt).	Tertiary (Mostly Post-Miocene).
Alaska	.....	29.7	.....	1.0	.....	7.8	.....	0.4
Arizona	.....	22.1	.....	20.0	.....	.....	2.0	2.2
California	.....	1,350.0	.....	30.0	.....	14.8	.....	1.0
Colorado	.....	.....	34.0	217.1	.....	.....	2.7	26.1
Idaho	.....	90.0	.....	22.8	.....	0.7	.....	1.0
Montana	.....	.....	200.0?	3.5?	.....	.....	4.7	
Nevada	.....	.....	20.0	230.0	.....	.....	?	2.0
New Mexico	.....	.....	7.6?	10.0?	.....	.....	0.4	0.4
Oregon	.....	54.0	.....	0.5?	.....	1.7		
South Dakota	74.0	.....	.....	16.0	3.8	.....	.....	2.4
Utah	.....	.....	25.0	2.0?	.....	.....	4.0	?
Washington	.....	10.0	.....	11.4	.....	0.2	.....	0.5
Wyoming	1.0	.....	.....	.....	0.1			
Appalachian States (Mainly Georgia and the Carolinas.)	47.0	.....	.....	.....	0.3			
	122.0	1,555.8	286.6	564.3	4.2	25.2	13.8	36.0
British N. America								
Nova Scotia	13.7	.....	.....	.....	0.6			
Quebec	2.0?							
Ontario	1.2?	.....	.....	.....	0.3			
British Columbia	.....	70.7	.....	.....	.....	4.7		
N. W. Territory	.....	52.6	.....	.....	.....	22.3		
	16.9	123.3	.....	.....	0.9	27.0		
Mexico	.....	40.0?	.....	160.0?	.....	2.0?	.....	7.0?
Total	138.9	1,719.1	286.6	724.3	5.1	54.2	13.8	43.0

NOTE TO TABLE II.—It should be expressly stated that this table is only a first tentative estimate, as in very many cases the data for exact subdivision are not available. The distribution for 1900 is, of course, probably more nearly correct than the segregation of the total product attempted in the first part of the table.

Discussion.

(*Trans.*, xxxiii., 1077.)

Willet G. Miller, Toronto, Canada: With regard to Mr. Lindgren's impression that the gold-supply of the world will gradually decrease if no further important improvements are made in the processes of gold-extraction, it seems to me that no very important improvements are needed to keep up the present production for many years to come. In many regions there are large deposits of auriferous material which can be worked if present conditions are slightly changed. In the territory occupied by the Archæan protaxis of the Province of Ontario, for instance, there are gold-deposits of large size which apparently could be worked at a profit if the cost of production were slightly decreased. Many of these deposits average approximately from $1 to $1.50 per ton, and consist of quartz veins, shattered, impregnated masses of granite and other rocks, and placer-deposits.

In the Rainy River district, in Western Ontario, gold occurs in a mass of rock which is thus described in the government reports of the Province: "It consists of a mixture of altered granite, quartz, and chlorite, with streaks of green schist. It has been traced 3 or 4 miles, and has a general direction of northeast and southwest. The boundaries are rather indefinite, but as near as can be ascertained it is 462 ft. wide at the widest known place. On the location we are dealing with it varies in width from 100 to 200 ft. One hundred feet is its width at the narrowest place, as far as known."[6] Judging from careful tests which have been made, much of this rock-matter contains $1.50 value per ton in free-milling gold. It has not been found possible, however, to work it at a profit.

Gold has been found in the Vermilion River placers, north of Sudbury, in a territory covering many square miles.[7] The metal occurs free, usually in a state of very fine division, and inclosed in pebbles of quartz. Fire-assays show that the sand and gravel frequently carry a value of more than $2 per ton. Much of the material, while lower in value, averages from 12 to 15 cents per cubic yard. While the existence of these placers

[6] *Seventh Report of the Ontario Bureau of Mines*, pp. 65, 130 and 131 (1897).

[7] *Idem*, pp. 256 to 259; *Tenth Report*, pp. 151 to 159 (1901).

has been known for some years, success has not been achieved in treating them. It would seem, however, that a comparatively slight improvement in the present methods of treatment should bring about the profitable working of them.

A year or two ago similar placers were discovered on Savant lake, which is about 150 miles northwest of Port Arthur and 500 miles from the last-mentioned area. In panning these sands and gravel I obtained a very few colors. Fire-assays, however, show that much of the material, which consists of coarse sand, gravel, and boulders, averages about $1 per ton in gold.[8] Some of the metal contained in the fragments of rock probably could not be extracted by free-milling processes. Similar deposits, which have not been examined as to their gold-content, cover a large territory in this little-explored region, and it would appear that the metal is present in most of this gravel.[9] In the vicinity of Savant lake the thickness of the sand- and gravel-deposits is at some points over 100 ft. The deposits are of glacial origin, and the average of the gold-content of the gravel from the tops of the higher hills is similar to that found at lower levels.

The rocks over a great part of the Archæan area of Canada are similar in character, and there is reason to believe that gold-deposits carrying values like those mentioned occur widely extended over this vast, imperfectly-explored region. It may be many years, probably not till the production of the richer deposits of other parts of the world begins to decline, before these deposits are worked. Since the gold-values which they carry, however, are so close to those of deposits which even now are being profitably worked, it is within the range of probability that the Canadian protaxis will, in the years to come, be the scene of a great gold industry. Low-grade deposits in other parts of the world also will then add their quota, and the day of a great decline in gold-production, a time of "not only physical devastation, but moral and political decay," thus seems far distant.

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[8] *Twelfth Report of the Ontario Bureau of Mines* pp. 89, 90 (1903).

[9] *Summary Report of the Geological Survey of Canada*, pp. 92 to 93 (1901).

W. L. AUSTIN, New York, N. Y.: In Mr. Lindgren's instructive paper the statement is made in the reference to the pre-Cambrian gold-quartz veins of South Dakota and Wyoming, that these two "are the only localities in the Cordilleran region in which pre-Cambrian deposits have been recognized." Further along in the paper [Part III., not reprinted here] it is stated that "gold-deposits of Archæan age are not known in Colorado. As far as the age has been determined, the deposits are divided into a smaller Mesozoic and a much greater Tertiary and probably chiefly post-Miocene group."

Mr. Lindgren has apparently overlooked an extensive auriferous deposit described by Messrs. E. C. and P. H. van Diest in a paper read before the Colorado Scientific Society in 1894. As the article referred to is not readily accessible, and as the said deposit is of considerable extent—the beds cropping out 3 miles in one direction, and 1 mile in another—a few extracts from the van Diest paper may be considered pertinent in discussing "The Geological Features of the Gold-Production of North America." Furthermore, this matter has commercial importance, for these beds may become at an early day a not-inconsiderable source of the precious metal.

The van Diests refer to this deposit as Cambrian; but it is thought that no serious attempt has been yet made to fix the age other than approximately. It is apparently lower than the Silurian, and in some respects resembles the pre-Cambrian deposits of the Black hills.

Quoting from the van Diest paper: "The district examined is on the Rito Seco. This little stream unites with the Rio de la Culebra near San Luis—the county seat of Costilla county—a region nearly in the center of the lower neck of the Pliocene lakes, named by Endlich the Coronados lakes. Leaving San Luis, the Rito flows for about 6 miles in a northerly direction through scattered *débris*, when the lake beds forming the foot hills are reached. Here the road takes an easterly direction, winding its way for about 3 miles through a wide and shallow canyon which has been eroded from the lake beds. According to Hayden the lake beds at this point should lie against the Upper Carboniferous. No dark-red sandstones, such as were observed in coming over Veta Pass, could be seen anywhere, but we found instead, on the north side of the Rito for a dis-

tance of a quarter of a mile, some quartzite beds forming steep cliffs, while further along the stream flows over light-colored limestones and finally over granite.

"Directly north of the creek a thin bed of conglomerate appears. It is composed of light-bluish and greenish quartz pebbles cemented by oxides of iron and manganese. Resting on this bed follow layers of quartzites whose total thickness is estimated at 160 ft. These quartzites are saccharoidal in appearance, of pure white color when freshly broken, but stained by a film of iron oxide where they have been exposed to the influence of the weather. The quartzites are succeeded by a thin bed of argillaceous shale, and the whole section is topped by layers of light-grey siliceous limestones for about 200 ft., where a quartzy parting separates them from others of somewhat darker color. . . . Although no fossils have been found as yet in the described beds, it is clear from a stratigraphic point of view that the limestones are of Silurian and the quartzites of Cambrian age.[10] An igneous dike about 30 ft. in width runs through the limestone beds in a northerly and southerly direction. It is of a dark purplish-brown color, very compact and fine grained. In appearance it resembles more the older basalt occurring between the lake beds, and is distinctly different from the younger basaltic overflow which caps the beds south and west of the Rito Seco. The dike had had no disturbing influence whatever on the limestone beds, as is shown by the cuts run into the limestone on either side of the dike. Northerly and higher up on the mountain a light-colored porphyry was observed, but owing to lack of time there was no opportunity afforded to determine what the extent of this eruptive mass might be, and what connection, if any, it might have with the dike, nor could we determine if, in an easterly direction, other quartzites and limestones rest on the granite. . . .

"Close inspection of the rusty faces of the quartzite cliff has lately revealed that three distinct layers of auriferous iron pyrite occur between the quartzite beds, the lower one measuring about 12 ft. in thickness, the next about 14 ft., and the upper one 8 ft. At the time of our visit a drift had been run

[10] As Cambrian conglomerates bear witness to pre-Cambrian gold-veins, then these deposits must be pre-Cambrian in the same sense as those of the Black hills.

in the middle seam for a distance of 40 ft. The breast and sides of this drift stood in almost solid pyrite. This pyritic ore as broken down assays from $5 to $15 in gold per ton. So far no copper-, zinc-, or other sulphides have been observed with the deposit. The field, although but little employed, seems to be of promise, and it is to be hoped that development work will be uninterruptedly prosecuted."[11]

Since the above was written these quartzite-beds have been exploited somewhat further; and it is now thought that the beds are more nearly an arkose than quartzite. This deposit is so little known that it is not surprising it should have escaped Mr. Lindgren's notice.

[11] *Proceedings of the Colorado Scientific Society*, vol. v., pp. 76 to 80.

No. 17.

Osmosis as a Factor in Ore-Formation.

BY HALBERT POWERS GILLETTE, NEW YORK, N. Y.

(New York Meeting, October, 1903. *Trans.*, xxxiv., 710.)

FROM the known laws of physical chemistry I believe it can be shown that progressive mass movement of water solutions in channels has seldom been the means of ore-concentration in veins. It is my purpose in this paper to show that the force known as "osmosis" has been the principal factor in ore-formation. Convection-currents have doubtless supplemented osmosis, and the two working together have been the agencies that have gathered the scattered particles of rare minerals into the larger masses which are called ore.

Osmosis is commonly thought of as a vague, feeble force that causes slow diffusion of dissolving matter through the solvent. That it is a measurable force, often of great intensity, few know, except those who are familiar with the laws of modern physical chemistry. Therefore, I may be pardoned for going briefly into the elementary mathematics of osmotic pressure and of convection-currents.

The velocity of water moving through any channel is given by the Chézy formula:

(1) $v = c\sqrt{rs}$, in which r is the hydraulic mean radius; s, the slope of the channel in which gravity is the sole propulsive force; and c, the coefficient of roughness of the sides of the channel.

From this formula it is evident that the smaller the channel, the smaller the velocity of water under a constant head. In rock-crevices, therefore, where the head is constant, water moves much more slowly than in large fissures, and in moving through sand or porous rock it is to an even greater degree retarded. Hence, if a mass of water-saturated sand be heated, the finer the sand-grains, the more slowly will the temperature rise at parts remote from the source of heat. Conversely, cooling is retarded the smaller the interstices or channels through which the convection-currents move. The importance of this

fact will appear later. Osmosis is the force which drives a solute through a solution. When a substance dissolves it behaves in many respects exactly as if it were vaporized. In fact, it has been proved by Van't Hoff that "The osmotic pressure of a substance in solution is the same pressure which that substance would exert were it in gaseous form at the same temperature and occupying the same volume."[1]

Expressed mathematically the law is:

$$(2)\quad p = \frac{RT}{V}$$

in which, p = osmotic pressure in pounds per square inch.
R = the gas constant = 1,206 lb. per sq. in.
T = absolute temperature = t° (Centigrade) + 273.
V = volume of the solvent containing one molecular weight of the solute.

$$(3)\quad V = \frac{100\,M}{r}$$

in which, M = sum of the atomic weights of the atoms in a molecule of the substance.
r = the rate per cent. of the solution.

Hence:

$$(4)\quad p = \frac{1{,}206\,r\,(t° + 273)}{100\,M} = \frac{12\,r\,(t° + 273)}{M}.$$

I have deduced equation (4) for convenience in ascertaining and comparing osmotic pressures. Thus, sugar is $C_{11}H_{22}O_{11}$. Hence for sugar, $M = (12 \times 11) + (1 \times 22) + (16 \times 11) = 342$. For a 2-per-cent. sugar solution, $r = 2$. Therefore at 15° C. we have the osmotic pressure according to equation (4) as follows:

$$p = \frac{12 \times 2\,(15 + 273)}{342} = 20.2 \text{ lb. per sq. in.}$$

By actual experiment p was found to be 20 lb. per sq. in. under these conditions; and Van't Hoff's law of osmotic pressure has been repeatedly proved by similar tests. From the above statement it is clear that osmosis is far from being a vague or feeble force.

When due to a rise in temperature, or for other reasons, ground-water at any given point begins to dissolve a mineral,

[1] *Elements of Physical Chemistry*, by J. Livingston R. Morgan, New York, John Wiley & Son, p. 96.

that mineral is immediately forced by osmotic pressure out to the extreme confines of the vessel holding the water. Let us suppose, therefore, that a dike-intrusion has so heated the surrounding waters that they have taken up a burden of PbS; evidently, then, osmosis will force this PbS throughout the mass of water into every cranny, crevice, fissure, or cavity. It requires no convection-currents to accomplish this distribution, although convection will hasten the process. Having taken up its full burden of PbS there comes a period of inactivity, until the temperature begins to fall. This fall of temperature will be most rapid near the surface of the earth and it will be most rapid in the larger water channels, for the reason that circulation there is least retarded.

In the case of dike-intrusion, I believe that the shrinking of the dike-matter will open the largest crevices and channels along the dike itself, and I conceive that surface-waters flowing into these shrinkage-cracks will accelerate the cooling near the dike. Hence, in such cases, contact ore-deposits will be found on one side of a dike, and that side will be the side which originally faced uphill. The down-flowing surface- or ground-water will enter the first crevices it meets and hasten the cooling there, and it is quite evident that where cooling is fastest, crystallization of dissolved mineral will first begin. Let the smallest speck of galena be crystallized out, and immediately osmosis will force more dissolved galena to that point, and thus feed the crystal-mass. Heretofore, the deposition of ore nearest the once-molten dikes has been inexplicable, but in no other place could it have started, and, once started, the tendency toward crystal growth must be due entirely to osmotic pressure

Let us consider for a moment certain other conditions that accelerate cooling, since it is now evident that much depends upon the first cooling of the solution. At the intersection of two fissures the cooling should be most rapid, for at that point two channels supply convection-currents. Hence the deposition of the most insoluble minerals should occur first at vein-intersections, a circumstance which is often verified in known ore-deposits. Again, in fissure walls that have been striated by slipping past one another, the grooves form channels in which convection-currents move most rapidly, and, as should be expected, the most insoluble minerals are found in the grooves.

This, I believe, explains "Clayton's law."[2] Since the richest minerals are ordinarily the most insoluble, I offer this general proposition: "Bonanzas should be sought at points where circulation has been freest, namely, in the widest and most open channels."

Since the relative solubility of minerals has evidently played so important a rôle in ore-formation, a few suggestions may not be out of place. Hot waters carrying metallic sulphides in solution must carry also a great burden of alkaline salts. In fact, the solubility of the metallic sulphides is due to the presence of these alkaline salts which form new ions with the sulphides, just as potassium cyanide dissolves gold salts by forming new ions with the gold. One well-known geologist has erred in assuming that the "solubility product" of every mineral is increased by the presence of other minerals in solution. This, in passing, I would say is not so; for it is only when new ions are formed with the added elements, that solubility is effected, and there are many minerals which do not combine to produce these new ions. The metallic sulphides and the ions formed by them have a very low "solubility product" at best, and when a lowering of temperature causes the sulphides to crystallize out, the "solubility products" of the substances in solution are often so increased that more country-rock is dissolved. In this manner for every particle of sulphide deposited by crystallization, a particle of country-rock may be dissolved. This, I take it, is the true explanation of the so-called "metasomatic replacement" which has been regarded as a true chemical reaction, or precipitation. I have never been able to believe that galena and other natural metallic sulphides are chemical precipitates, and one of my strongest reasons for this disbelief has been the fact that chemical precipitates of lead and similar sulphides are flocculent and never crystalline. How cubical galena could be precipitated chemically from solution, by any reducing agent in nature, has ever been a most serious stumbling block. I am convinced now that practically all of the hypothetical equations written by geologists to account for ore-deposition by chemical reaction are erroneous. Many of these equations can be demonstrated to be false from the laws of thermal chemistry, and few of

[2] *Ore-Deposits of the United States and Canada*, J. F. Kemp, p. 49.

them appear even plausible when viewed from a thermo-chemical standpoint. It is not now my purpose to tear down, but to build up. I am wholly in accord with Professor Kemp and other geologists who voice the movement against the chemical theories of ore-deposition which have so long occupied the arena. It cannot be denied, however, that very many ore-deposits have come from minerals carried in solution to the chambers where they are now found.

It has been urged in the past that the formation of ore-deposits from hot-water solutions could not have occurred, for two reasons: (1) Because the same heat that would cause the solution of the precious minerals would also cause the solution of the rocks in which those minerals are scattered, and conversely, cooling would precipitate them both together, and, (2) Because hot springs are not now depositing metallic sulphides except in very small amounts and then only in the midst of a mass of gangue.

I trust that I have indicated how osmosis effects the distribution and final concentration of minerals, without any appeal to hot-water-spring theories or to chemical precipitation from cold-water theories, for I am convinced that we must look to the laws of physical chemistry for an explanation of ore-formation, and not to the laws of physics or of chemistry alone.

No. 18.

The Ore-Deposits of Su dbury, Ontario.*

BY CHARLES W. DICKSON, COLUMBIA UNIVERSITY, NEW YORK, N. Y.

(Albany Meeting, February, 1903. *Trans.*, xxxiv., 3.)

CONTENTS.

	PAGE
PART I. THE RELATION OF NICKEL TO PYRRHOTITE,	455
Introduction,	455
Minerals of the Sudbury Nickel-Region,	456
Pyrrhotites in General,	458
The Origin of Pyrrhotite,	460
Nickel and Cobalt in Pyrrhotite,	461
The Sudbury Pyrrhotites,	463
The Magnetic Separation of Nickeliferous Pyrrhotite,	466
The Nickel-Bearing Mineral,	470
The Non-Magnetic Residue,	472
The Formula of the Pyrrhotite,	475
Summary,	476
PART II. GENESIS OF THE SUDBURY ORES,	477
General Considerations,	477
Classification of Pyrrhotites,	477
Value of the Classification,	478
The Sudbury Pyrrhotite-Deposits,	479
The Nickel-Belts,	480
Various Theories of the Origin of Nickeliferous Pyrrhotite,	481
The Rossland Pyrrhotite-Deposits,	486
Microscopical Evidence of the Origin of the Ores,	497
Sudbury District,	497
Wallace Mine,	508
Rossland, B. C.,	509
Ducktown, Tenn,	510
Summary,	510
Relation of Chalcopyrite to Pyrrhotite,	513
Source of the Metals,	514
Acknowledgments,	516

I. THE RELATION OF NICKEL TO PYRRHOTITE.

Introduction.

The Sudbury district is to-day one of the two great sources of nickel in the world. The peculiar geological relations of

* This paper was presented by the author as a dissertation for the degree of Ph. D. at Columbia University, New York City.

the ores have long attracted attention, and widespread interest has been aroused by the difference of opinion regarding their origin, whether as igneous segregations or as precipitates from solution. The writer has endeavored to attack this problem with the aid of microscopical and petrographical methods. The field-work of these investigations was carried on during the summers of 1901 and 1902, and the material collected was worked up at Columbia University, New York, during the sessions of 1901–02 and 1902–03.

As a necessary preliminary, it was thought advisable to investigate carefully the chemical composition and geological relations of pyrrhotite, as well as the mineralogical associations of the Sudbury ores.

Minerals of the Sudbury Nickel-Region.

Pyrrhotite and chalcopyrite, associated with fragments of the inclosing rock, are the predominant minerals of the Sudbury deposits. The nickel-mineral pentlandite, which is the principal source of this metal, is distributed through all the ore-bodies in greater or less amount. Its matrix is almost universally pyrrhotite, though a number of exceptions occur, notably at the Copper Cliff mine.

This mine, which has furnished a number of interesting minerals, contains in the lower levels some massive ore, composed very largely of chalcopyrite intimately associated with pentlandite. Other samples from the same place consist of pyrite and marcasite, also with an intimate mixture of pentlandite.

Millerite is encountered, though rarely. In a sample from the Copper Cliff mine, the writer found small bunches of hair-like crystals of this mineral in the cavities of some radiating pyrite mixed with calcite. It has also been reported in a number of other cases. The millerite is undoubtedly secondary, and was probably derived from pre-existing pentlandite.

Polydymite (Ni_4S_5, with one part of nickel replaced by iron) containing platinum was described by Clarke and Catlett.[1]

Niccolite, gersdorffite, danaite, and arsenopyrite (containing cobalt) occur in several localities in Denison township, though

[1] *American Journal of Science*, Third Series, vol. xxxvii., No. 221, p. 372 (May, 1889).

the association is not exactly similar to that of the typical deposits.

Pyrite is by no means uncommon, and Walker has described a nickeliferous variety (over 4 per cent. of nickel) from the Murray mine. A number of samples of this mineral from the Copper Cliff mine were associated with secondary quartz, calcite, and millerite. On analysis, they yielded from a trace to over 3 per cent. of Ni, which, however, may be due to an intimate mixture of pentlandite or millerite.

Samples of a compact, whitish or steel-gray mineral, containing a considerable amount of pentlandite, were submitted by the writer to Professor Penfield, who considers it to be massive marcasite. The analyses conform to the formula FeS_2, and show the presence of from 2 to 4 per cent. of Ni, probably as pentlandite.

Sperrylite ($PtAs_2$) was originally found in the gossan at the Vermilion mine. The writer has also isolated it from the unaltered chalcopyrite of the Victoria mine (see p. 463).

Galena occurs rarely in streaks through the pyrrhotite, *e. g.*, at the Mount Nickel mine, Blezard township.[2]

Native copper is reported in a few instances in leaves in the associated rocks. Secondary copper-minerals are rare; but bornite is occasionally seen.

Small masses of titaniferous magnetite (with as much as 18 per cent. of TiO_2) are at times found.

This list is probably not complete, but represents the most important minerals found by the writer or recorded by others.

S. H. Emmens[3] describes what he calls several new species of nickel-minerals from Sudbury. But the doubtful purity of his material and the analytical methods employed do not warrant the recognition of these new species.[4]

As a preliminary to the discussion of the relation of the nickel to the pyrrhotite and its associates, a brief review of our knowledge of pyrrhotites will be given; since the uncertainty

[2] Specimen kindly furnished by Prof. W. G. Miller, Provincial Geologist of Ontario.

[3] *Journal of the American Chemical Society*, vol. xiv., p. 205 (1892).

[4] S. L. Penfield, On Pentlandite from Sudbury, Ont., Can., with Remarks upon Three Supposed New Species from the Same Region, *American Journal of Science*, Third Series, vol. xlv., No. 270, p. 493 (June, 1893).

which prevails regarding the exact chemical composition of pyrrhotites is probably not generally appreciated by students of ore-deposits.

Pyrrhotites in General.

For many years the composition of pyrrhotite has presented to chemists and mineralogists a most difficult and interesting problem, to a large extent still unsolved.

Various writers have applied to this mineral formulas which range from Fe_3S_4 to $Fe_{16}S_{17}$. In general terms it is usually expressed as Fe_nS_{n+1}. By some it is regarded simply as FeS with impurities.[5] Others consider it as varying molecular mixtures of different sulphides, as $nFeS + Fe_2S_3$ or $nFeS + FeS_2$. Bodewig's [6] and Doelter's [7] formula was $Fe_{11}S_{12}$.

In other words, "pyrrhotite" is regarded, not as a mineral in the true sense of the term, but as a series of minerals, differing slightly from each other in the relative proportions of their constituents. If this is the correct view, the case is unique. Homologous chemical series are by no means uncommon, but in these there is always a gradual change in the properties of the different members; the extremes being so entirely unlike as hardly to be recognizable components of the same group. There seems, however, to be little, if any, difference between pyrrhotites represented by Fe_3S_4 and $Fe_{16}S_{17}$. It should thus be possible to grade imperceptibly from the monosulphide, FeS, to the disulphide, FeS_2, when a pyrrhotite with the composition of pyrite would result. But such a view does not seem reasonable, and is opposed to some of the fundamental laws of chemistry. It seems more reasonable to consider many of the so-called "pyrrhotites" as mixtures of other sulphides with this mineral, and to regard the latter as of a definite composition.

A fact which may have an important bearing on this question is that of the magnetic permeability of different pyrrhotites. In the preparation of various samples, as noted later in this paper, some were observed to be much more magnetic than

[5] Weinschenk, Groth's *Zeitschrift für Krystallographie und Mineralogie*, vol. xvii., p. 499; Lorenz, *Ber. d. chem. Ges.*, p. 1501 (1891).

[6] Groth's *Zeitschrift*, vol. vii., p. 180.

[7] Tschermak's *Mineralogische und petrographische Mittheilungen, N. F.*, vol. vii., p. 544. A synopsis of the results obtained by different writers will be found in the *Handbuch der Mineralogie*, Hintze, vol. i., p. 621 *et seq.* (1901).

others, the strength of attraction by a small magnet being, in a general way, proportional to the percentage of iron. Further investigation along this line may lead to important results.

It should be borne in mind, however, that lack of care in the preparation of samples for analysis may account for many discrepancies, especially as few pyrrhotites are entirely free from other sulphides in more or less intimate mixture.

The inaccurate methods of analysis, and difficulties of manipulation, will also cause many errors. That the reliability of many analytical methods is open to question is shown by the animated controversies of experts in recent years.[8] Errors amounting to 0.75 per cent. in the estimation of sulphur are not uncommon, and in many cases they are possibly larger. The iron-results are also apt to be unreliable.

In a number of determinations on the same sample Habermehl[9] obtained results in which the sulphur varied from 39.10 to 39.71—a difference of 0.61, and iron from 60.28 to 60.79—a difference of 0.51 per cent. When we consider the theoretical compositions represented by the compounds varying from FeS to FeS_2 it is seen that a comparatively small error would change the formula calculated from the analysis. The calculated composition for different formulas would be as follows:

Formula.	Iron. Per Cent.	Sulphur. Per Cent.	Formula.	Iron. Per Cent.	Sulphur. Per Cent.
FeS . .	63.61	36.39	Fe_8S_9	60.80	39.20
$Fe_{15}S_{16}$ . .	62.06	37.94	Fe_7S_8	60.40	39.60
$Fe_{11}S_{12}$ . .	61.60	38.40	FeS_2	46.60	53.40

A few analyses made by prominent workers (see Table I.) will show the wide variation, both in the analytical results and in the recorded specific gravity of the mineral. The latter varies very widely (3.98 to 4.80) and probably indicates the doubtful purity of the sample. Where the total (as in analysis No. 1) is over 101 per cent., any calculations based on the result will be wholly misleading, and it is safe to say that many others recorded, while not indicating such an excess, are equally unreliable for this purpose.

[8] Gladding and Lunge, *Journal of the American Chemical Society*, vols. xvi., xvii., and xviii. (1894 to 1896).

[9] *Oberhessische Gesellschaft für Natur- und Heilkunde*, vol. xviii., p. 97 (1879).

TABLE I.—*Analyses of Pyrrhotite.*

	1.	2.	3.	4.	5.	6.	7.	8.	9.
Fe	63.82	63.15	63.35	62.62	63.41	62.04	61.17	60.83	58.00
S	37.36	36.35	35.91	37.38	36.29	38.08	38.83	39.17	42.00
Total	101.18	99.50	99.26	100.00	99.70	100.12	100.00	100.00	100.00
Sp. gr.	3.98	4.62	4.787	4.80	.....	4.497	4.546	4.580	
Formula	Nearly FeS.	Nearly FeS.	Nearly FeS. (Fe in excess.)	Nearly FeS.	FeS.	$Fe_{12}S_{14}$.	Fe_9S_{10}.	Fe_8S_9.	Fe_4S_5.

No. 1. Nenntmansdorf, Geinitz, *N. Jahr.*, 1876, 609.
No. 2. Tavetsch, Gutknecht, cited by Kenngott, *N. Jahr.*, 1880, 1, 164.
No. 3. Seeläsgen, Rammelsberg, *Pogg. Ann.*, 1864, cxxi., 368.
No. 4. Brazil, Berthier, *Ann. Mines*, 1835, vii., 531.
No. 5. Jeliza, Servia, Losanitsch, *Ber. d. Chem.*, 1892, xxv., 880.
No. 6. Borév, Pálfy, Groth's *Zeit.*, xxx., 184, and xxvii., 101.
No. 7. Bodemais, Graf Schaffgotsch, *Pogg. Ann.*, 1840, l., 533.
No. 8. Hartzburg, Rammelsberg, *Pogg. Ann.*, 1864, cxxi., 356.
No. 9. Chile, Mennier, *Cosmos*, 1869, 3d series, v., 581.

The above results are taken from C. Hintze's *Hdb. der Min.*, vol. i., pp. 653 and 654 (1901).

Altogether apart, however, from the considerations outlined above, pyrrhotite, as we know it, is not constant in composition; and an adequate explanation of the variations in its composition is one of the problems of the future.

The Origin of Pyrrhotite.

Little is known of the conditions under which pyrrhotite is formed in nature, except that a strongly-reducing atmosphere is necessary. Those synthetic reproductions of the mineral, which have not been made under conditions analogous to those of nature, do not aid materially in explaining its origin.

Doelter,[10] however, by heating ferrous chloride to 250° C. in an atmosphere of carbonic acid and hydrogen sulphide gas, produced pyrrhotite much like the natural mineral and having a composition represented by $Fe_{11}S_{12}$. He also produced it by the action of H_2S gas on solutions of ferrous sulphate, carbonate, chloride, and silicate. Other methods of preparation do not appear to have any direct bearing on the natural formation of the mineral.

[10] Tschermak's *Mittheilungen*, vol. vii., pp. 85, 86.

Nickel and Cobalt in Pyrrhotite.

Nickel is universally recognized as an associate of pyrrhotite, and in few cases has it proved, when looked for, to be entirely lacking. Whether the nickel is an essential constituent of the pyrrhotite, replacing part of the iron, or whether it is present as a separate compound, is still a disputed question. It is hoped, however, that the results here presented will help to clear this matter up to a great extent.

The percentage of nickel varies widely in different pyrrhotites. Those occurring in metamorphosed sedimentary and acidic schistose rocks are notably low in nickel, while in those associated with basic igneous rocks, especially of the gabbro family, it may range from a trace to a proportion economically valuable. Cobalt nearly always accompanies the nickel, though usually in very subordinate amount.

Tables II., III., and IV. give the nickel-contents of representative pyrrhotites of these two classes. Those of the first class rarely carry more than 0.5 per cent. of nickel, while those from basic eruptives usually exceed this limit, some of the Rossland examples being notable exceptions.

TABLE II.—*Percentages of Nickel and Cobalt in Pyrrhotites Generally.*

	Ni.	Co.		Ni.	Co.
ONTARIO.			BRITISH COLUMBIA.		
1. Dalhousie twp. Lanark co...	0.23	trace	1. West Kootenay	0.16	0
2. Dalhousie twp. Lanark co...	0.11	trace	2. Kennedy Lake, V. I.	0.16	trace
3. Anglesea twp. Addington co.	0.16	trace	3. Deer Creek, V. I.	1.70	trace
4. Galway twp. Peterboro' co..	0.16	trace	4. West Kootenay	0.14	trace
5. Galway twp. Peterboro' co..	0.10	trace	5. Crawford Bay	0.05	trace
6. Galway twp. Peterboro' co..	0.05	trace	6. Jarvis Island	0.28	trace
7. Victoria co	0.15	trace	7. Rossland	0.23	trace
8. Rainy River District	0.13	trace	8. Rossland	0.13	trace
9. District of Nipissing	3.30	trace	9. Kootenay Lake	0.68	trace
10. District of Nipissing	2.10	trace	SWEDEN, ETC.		
QUEBEC.			1. Klefva	1.08	0.07
1. Ottawa co	0.13	0	2. Klefva	1.50	0.08
2. Ottawa co	1.68		3. Klefva	2.03	0.10
3. Calumet Island	1.48		4. Sagmyrna	0.50–0.80	
4. Calumet Island	4.06	0.33			
5. Pontiac co	1.50	trace	5. Krageroe	1.75	
NOVA SCOTIA.			6. Varallo	1.20–1.44	
1. Cape Breton co	0.10	trace			
NEW BRUNSWICK.			UNITED STATES.		
1. St. Stephen	1.82	0.17	1. Gap Mine, Pa.	1.75	0.10
2. St. Stephen	trace to 4.00		2. Gap Mine, Pa.	1.00–3.00	
			3. Anthony's Nose, N. Y.	0.30	

NOTE.—The nickel-mineral gersdorffite occurred in association with some of these pyrrhotites, so that in part the nickel found may mean an admixture of this mineral.

Ontario.—1. Pyrrhotite with pyrite in white translucent quartz and hornblende; 2. Pyrrhotite with pyrite in quartz-mica-diorite (Nos. 1 and 2 occur in dark-gray diorite, which cuts gneiss); 3. Pyrrhotite in dark-gray gneissoid rock; 4. Massive pyrrhotite; 5. Massive pyrrhotite with pyrite, chalcopyrite, and quartz; 6. Massive pyrrhotite with chalcopyrite, quartz, and feldspar (other samples from Galway gave from a trace to 0.15 per cent. of nickel. The pyrrhotite is associated with bands of gneiss, mica-schist, and quartzite; *i. e.*, the deposits are *fahlbands*, like those of Norway, which are likewise poor in nickel); 7. Massive pyrrhotite; 8. Massive pyrrhotite with a small amount of quartz from the Huronian schists of English river; 9 and 10. Pyrrhotites with small amounts of chalcopyrite in a gangue of grayish-green diorite. (Pyrrhotites occurring in light- and dark-gray gneissoid rocks from Frontenac county, Ont., Schreiber (Thunder bay), Darlington bay (Lake of the Woods), and numerous other localities all contained nickel, but only in traces.)

Quebec.—1. Massive pyrrhotite from Eardley township; 2. Pyrrhotite in part massive, in part disseminated through a gangue of quartz, feldspar, and hornblende; 3. Small quantity of pyrrhotite, etc., in a quartz-amphibolite; 4. Massive pyrrhotite with a little quartz gangue (the associated rocks of 3 and 4 are diorites, which cut a series of gneisses and limestones); 5. Massive pyrrhotite.

Nova Scotia.—Pyrrhotite in a siliceous gangue from Leitche's creek.

New Brunswick.—Pyrrhotite with a little chalcopyrite and a small amount of quartz gangue, or diorite and quartz. (The association is much like that of Sudbury. Various samples from the same locality yield from a trace to 4 per cent. of nickel.)

British Columbia.—1. Pyrrhotite in quartz, feldspar, and hornblende; 2. Massive pyrrhotite in a gangue of quartz, garnet, calcite, and hornblende; 3. Massive pyrrhotite with chalcopyrite in a quartzose gangue (from the Two Sisters and Crow claim); 4. Pyrrhotite and chalcopyrite in a dark-green rock; 5. Pyrrhotite in association with a small amount of chalcopyrite, graphite, quartz, mica, and feldspar; 6. Pyrrhotite with chalcopyrite in a gangue of quartz-green diorite; 7 and 8. Massive pyrrhotite with chalcopyrite in massive eruptive rocks, the ore-bodies lying between gabbros and surrounding porphyries and diabases; 9. Pyrrhotite with pyrite and chalcopyrite in garnet and quartz.

The above Canadian examples are taken from vols. vi. to xi. of the *Reports of the Canadian Geological Survey.*

Sweden, etc.—Pyrrhotites in dark eruptive rocks, principally gabbros (authority, Schnabel's *Handbook of Metallurgy.*)

Gap Mine, Pa.—Pyrrhotite with chalcoyrite, pyrite, etc., in the outer portions of basic igneous rock-masses, which may be metamorphorsed to amphibolites.

Mine at Anthony's Nose, N. Y.—Pyrrhotite in association with feldspar, pyroxene, hornblende, and quartz; the walls being acidic gneisses. (Authority for this and the preceding examples, The Nickel-Mine at Lancaster Gap, by J. F. Kemp, *Trans.*, xxiv., 620, 883, 1894.)

The relation of the nickel-content to the mode of origin of the pyrrhotites and the inclosing rock will be considered subsequently.

One of the purposes of this investigation has been to test the validity of the view generally held, that in the Sudbury pyrrhotites the nickel and cobalt replace the iron isomor-

phously. Another purpose has been to try to find a definite formula for the sulphide of this district, with the idea of comparing it with similar minerals from other localities.

The Sudbury Pyrrhotites.

The Sudbury nickel-region, as treated in this paper, will be considered, for convenience, as including the deposits of similar nature in the adjoining Algoma district, as well as those in the immediate vicinity of the town of Sudbury.

The ore mined in this region consists chiefly of a mixture of pyrrhotite and chalcopyrite, intimately associated with more or less country-rock. The pyrrhotite carries the nickel, while the chalcopyrite appears to be quite free from that element.[11] Table III. gives the nickel and copper in typical samples of the ore of some of the leading Sudbury mines, as taken from the catalogue of the Ontario mineral exhibit at the Buffalo Pan-American Exposition of 1901, and similar data regarding a number of nearly-pure pyrrhotites from claims in various parts of Algoma, taken from the reports of the Canadian Survey. These Algoma deposits have the same geological relations—*i. e.*, they are closely associated with an altered gabbro or norite.

The average contents of nickel, copper, and cobalt in the ore smelted since 1892 are given in Table IV. The statements of Messrs. Turner and Walker, Table V., show that gold, silver, and the metals of the platinum group are constant constituents of the ore, though present only in small quantities.

Sperrylite, the arsenide of platinum ($PtAs_2$), was first recognized in the decomposed products of chalcopyrite and pyrrhotite at the Vermilion mine. The platinum in the unaltered ore occurs as sperrylite, as proved by the writer.[12] T. L. Walker[13] has shown that the sperrylite is associated with the chalcopyrite, rather than the pyrrhotite. Recent investigations seem to confirm this view, as sperrylite has been found associated with copper-minerals in several other places.

[11] Thus, Nos. 3 and 5 in Table III., which are largely chalcopyrite, contain but little nickel.

[12] *American Journal of Science*, Fourth Series, vol. xv., No. 86, p. 137 (Feb., 1903).

[13] *Idem*, vol. i., No. 2, p. 110 (Feb., 1896).

Mr. Turner's estimate, given in columns A and B, Table IV., probably presents fair averages of the general run of the ore. The figures under A may give a good idea of the ore of the Creighton mine, while that from Copper Cliff may run up to 7 per cent. of copper and 3 per cent. of nickel, according to the particular level from which the ore was taken (copper predominating in the upper, and nickel in the lower levels). Column B is based on the composition of the matte produced, as shown in Table V., column I.

TABLE III.—*Nickel and Cobalt in Sudbury and Algoma Pyrrhotites.*

	Ni.	Cu.		Ni.	Cu.
	Per Cent.	Per Cent.		Per Cent.	Per Cent.
SUDBURY.			ALGOMA.		
1. Victoria mine	3.50	4.50	1. Lorne township	1.95	0
2. Copper Cliff mine	9.25	0.51	2. Lorne township	2.80	0
3. Copper Cliff mine	1.25	23.78	3. Nairn township	1.95	trace
4. Stobie mine	2.99	0.37	4. Drury township	2.01	trace
5. Stobie mine	0.64	24.23	5. Denison township	1.80	0
6. No. 2 mine	4.70	0.38	6. Levack township	4.13	
7. No. 2 mine	1.87	13.76	7. Levack township	3.00	trace
8. No. 3 mine. Frood	4.85	0.42	8. Levack township	1.96	trace
9. No. 4 mine	4.33	1.39	9. Morgan township	3.30	
10. No. 4 mine	4.15	2.49			
11. Creighton mine	7.03	1.81			
12. No. 2 extension	4.32	0.35			
13. Worthington mine	3.00	3.00			

NOTE.—The Sudbury figures are from the catalogue of the mineral exhibit of Ontario at the Pan-American Exposition of 1901, except those of the Worthington mine, which are the result of a number of analyses of average samples, obtained through the kindness of R. E. Booraem, New York City.

The Algoma figures are taken from reports of the Geological Survey of Canada. Most of the samples were massive pyrrhotite, with a small amount of chalcopyrite. The copper per cent. was not reported.

TABLE IV.—*Averages of Smelters' Assays of Sudbury Ores, from* 1892 *to* 1900.

	1892.	1893.	1894.	1895.	1896.	1897.	1898.	1899.	1900.	A.	B.
	Per Ct.	Per Ct.	Per Ct.	Per Ct.	Per Ct.	Per Ct.	Per Ct.	Per Ct.	Per Ct.	Per Ct.	Per Ct.
Cu, . .	3.19	2.38	3.14	2.73	2.54	2.86	3.43	.....	1.59	1.50	2.00
Ni. . .	3.36	2.21	2.92	2.67	2.67	2.08	2.28	.....	1.67	3.50	2.50
Co, . .	0.10	0.08	0.07								

NOTE.—The figures for the several years are taken from the *Sixth Report of the Ontario Bureau of Mines* (1896) and *Mineral Industry*, vol. ix. (1900). The returns for 1900 seem too low. Columns A and B, furnished by President A. P. Turner, of the Canadian Copper Co., contain (A) an estimate of certain ores of that company, and (B) a general average based on the composition of the matte produced from a mixture of all its ores.

TABLE V.—*Composition of Sudbury Mattes.*

	I.	II. Per Cent.
Copper,	14 per cent.	25.92
Nickel,	17 per cent.	48.82
Cobalt,	0.5 to 0.6 per cent.	
Gold,	trace	0.000075
Silver,	0.5 to 1 oz. per ton.	0.001775
Platinum,	0.25 to 0.5 oz. per ton.	0.000430
Palladium,	0.25 to 0.5 oz. per ton.	present
Iridium,	.....	0.000056
Osmium,	....	0.000057
Rhodium,	.....	present
Iron,	.....	2.94
Sulphur,	.....	22.50

I. Average furnished by President A. T. Turner for mattes of the Canadian Copper Co.

II. Analysis of the matte from the Murray mine, given by T. L. Walker, *American Journal of Science*, Fourth Series, vol. i., No. 2, p. 112 (Feb., 1896).

To ascertain as accurately as possible the average nickel- and cobalt-contents of the general run of the pyrrhotite from the whole region, a number of analyses of carefully-selected material were made by the writer.

The pyrrhotite was coarsely crushed and the mineral picked out as pure as possible, under a lens when necessary. From the massive varieties good samples were easily obtained; but in other cases the pyrrhotite was so intimately mixed with chalcopyrite and rock that it was very difficult to obtain satisfactory samples, some rock always adhering to the sulphide. The results, given in Table VI., show that the percentage of nickel and cobalt in the pyrrhotite, calculated to the pure mineral, is fairly constant over a wide area, embracing all the principal mines and prospects. The pyrrhotites include both coarse- and fine-grained massive varieties, and those mixed with more or less rock and chalcopyrite. The object was to determine, as far as practicable, only the nickel existing as a component of the pyrrhotite, if it occurred as such. In the case of the coarse-grained varieties, where the nickel-mineral pentlandite is often to be recognized, this was carefully rejected, as far as possible. But the difficulty of this separation accounts for the fact that some of these varieties show less nickel than the fine-grained ones, although the former are usually considerably richer. Had the coarse-grained samples been treated in their

original condition, the results would have been more uniform. Subsequent work proves that a large part, at least, of the nickel is not a constituent of the pyrrhotite. The results of these tests, therefore, represent the nickel which is most intimately associated with pyrrhotite and does not appear in visible particles of pentlandite.

Cobalt is always very subordinate in amount, bearing a ratio between 1 : 40 and 1 : 50 to the nickel.

TABLE VI.—*Nickel, Cobalt, etc., in Sudbury Pyrrhotites.*

Location.	Insol.	Cu.	Ni.	Co.	Ni in Pure Pyrrhotite.
	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.
1. Elsie (a)..	2.00	trace.	2.40	0.06	2.46
2. Elsie (b)	3.45	trace.	2.35	0.05	2.44
3. Stobie (a)	1.50	trace.	3.00	0.08	3.05
4. Stobie (b)	4.00	trace.	2.05	0.05	2.15
5. Frood, No. 3 mine (a)	0.40	trace.	2.35	0.05	2.40
6. Frood, No. 3 mine (b)	5.00	trace.	2.34	0.06	2.48
7. Mount Nickel	2.20	trace.	3.00	0.07	3.06
8. Copper Cliff, No. 4 mine (a)...	1.10	trace.	3.24	0.06	3.30
9. Copper Cliff, No. 2 mine (b)...	5.00	trace.	3.70	0.08	4.00
10. Copper Cliff, No. 5 mine (c)...	0.50	trace.	3.47	0.08	3.50
11. Creighton (a)	3.25	trace.	3.84	0.10	4.00
12. Creighton (b)	0.50	trace.	2.26	0.06	2.32
13. Gertrude (a)	5.00	trace.	3.83	0.11	4.05
14. Gertrude (b)	6.00	trace.	3.61	0.09	4.00
15. Victoria (a)	0.50	trace.	3.36	0.07	3.40
16. Victoria (b)	0.40	trace.	3.14	0.08	3.20
17. Levack	3.20	trace.	2.80	.....	2.88
18. North Range	4.10	trace.	2.22	.....	2.32

NOTE.—These analyses, and others by the writer, were made in duplicate or triplicate to insure the greatest possible accuracy.

1. Coarse pyrrhotite with a small amount of chalcopyrite and rock ; 2. Compact fine-grained pyrrhotite, with a small amount of rock ; 3. Massive fine-grained pyrrhotite ; 4. Pyrrhotite and chalcopyrite in diorite , 5. Pure, coarse pyrrhotite ; 6. Fine-grained pyrrhotite ; 7. Massive pyrrhotite ; 8. Coarse pyrrhotite. 9, 10, 11. Massive fine-grained pyrrhotite; 12. Coarse pyrrhotite ; 13, 14. Massive pyrrhotite ; 15. Massive fine-grained pyrrhotite; 16. Coarser than No. 15, but with more chalcopyrite; 17. Massive pyrrhotite (Tuff & Stobie's property) ; 18. Coarse, massive pyrrhotite from Wisner township.

The Magnetic Separation of Nickeliferous Pyrrhotite.

Many experiments have been performed in recent years to effect a commercial magnetic separation of the nickel in pyrrhotite ores; or, for scientific purposes, to determine the con-

dition of the nickel in this mineral. The commercial elimination of the nickel is probably an impossibility, and the scientific problem is only now approaching a solution.

S. H. Emmens [14] refers to the work of Habermehl (1879), who effected a separation of European nickeliferous pyrrhotite into magnetic and non-magnetic portions.

T. J. McTighe, in 1890, applied magnetic separation in the treatment of Canadian ores; and in 1892 T. A. Edison, in applying for a U. S. Patent, said:

"I have discovered that where magnetic pyrites, called pyrrhotite, is nickeliferous, as it usually is to a more or less extent, the nickel is not distributed generally throughout the whole body of the pyrrhotite, but certain crystals are pure pyrrhotite or magnetic pyrites, while other crystals have some of the iron replaced by nickel and sometimes by cobalt, and that the crystals containing the nickel and cobalt are considerably less magnetic than the pure pyrrhotite."

Emmens himself made some crude experiments on material from the Gap mine, Pa., and from Sudbury, and obtained two products, the non-magnetic being considerably richer in nickel than the original ore.

Shortly after, David H. Browne [15] contributed a very valuable article on the same subject. He shows the existence of a rich nickel-mineral in the ores from the Copper Cliff, Evans, and Stobie mines, in the Sudbury district, and also that it can be separated by rough-crushing and hand-picking, after first removing the magnetic part. His analyses [16] show that the non-magnetic residue bears a close resemblance to the pentlandite described by Penfield.

Probably the most extensive series of experiments for a commercial separation were those made by J. N. Judson, of the Wetherill Separating Co., in 1900. The results have never been published; but Mr. Judson has very kindly placed them in the hands of the writer, and a partial abstract is here presented.

The material operated on was nearly pure pyrrhotite from Copper Cliff, containing, by analysis, Ni, 3.14; Cu, 0.42; and Fe, 49.78 per cent. The magnetic-separation products, with

[14] *Second Report, Ontario Bureau of Mines*, p. 163 (1892). *Journal of the American Chemical Society*, vol. xiv., No. 10, p. 369 (1892).

[15] *Engineering and Mining Journal*, vol. lvi, No. 23, p. 565 (Dec. 2, 1893).

[16] Nos. 5 to 8 in Table XI. of this paper.

different current-strengths, and the analysis of each, are given in Table VII.

TABLE VII.—*Magnetic Separation of Pyrrhotite by the Wetherill Separator. First Experiment—Material Crushed to No.* 30 *Mesh.*

Product No.	Amperes.	Magnetic Product.	Analyses.					
			Magnetic Portion.			Total Percentage of Metal in Magnetic Portion.		
			Ni.	Cu.	Fe.	Ni.	Cu.	Fe.
		Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.
1	1	90.11	2.46	0.22	53.60	70.58	47.48	97.02
2	15	7.65	10.83	0.78	14.80	26.38	14.37	2.27
3	15	0.78	9.68	2.55	13.25	2.42	4.79	0.21
4	28	0.92	1.76	13.58	20.10	5.87	29.99	0.37
5	tails	0.54	0.70	2.64	11.25	0.13	3.35	0.12
1a	1	90.11	2.46	0.22	53.60	70.58	47.48	97.02
2-5a	.....	9.89	9.38	2.21	14.97	29.42	52.52	2.98

[a] Making only two products—*i. e.*, magnetic and non-magnetic—at 1 ampere.

The results show that with a current-strength of 1 ampere 90.11 per cent. of the total sample was magnetic, and this contained 2.46 per cent. of Ni, or the equivalent of 70.58 per cent. of the total metal in the original pyrrhotite; that is, only 29.42 per cent. of the total nickel was concentrated in the non-magnetic portion (making only two products). The second and third products (15 amperes) were highly nickeliferous; but as they contained less than a third of the total nickel in the ore, the loss in the magnetic portion was very heavy.

In the next experiment, the first magnetic product, at 1 ampere (amounting to 90.11 per cent. of the total), containing Ni, 2.46; Cu, 0.22; and Fe, 50.62 per cent., was again treated, using a weaker current. The results are shown in Table VIII.

TABLE VIII.—*Magnetic-Separation Product No.* 1 *of Table VII. Second Experiment* (*No.* 30 *Mesh*).

Product No.	Amperes.	1. Magnetic Portion of Part Treated.	2. Magnetic Portion of Total.	Analyses.		
				Ni.	Cu.	Fe.
		Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.
1	$\frac{2}{16}$	33.61	30.28	1.93	0.08	56.65
2	$\frac{3}{16}$	54.15	48.79	2.08	0.13	55.60
3	$\frac{4}{16}$	4.64	4.18	3.46	0.18	53.00
4	$\frac{8}{16}$	1.79	1.61	3.70	0.51	41.25
5	1	2.35	2.12	3.95	0.90	23.80
6	tails	3.47	3.13	10.60	2.44	20.20

Column 1 gives the percentage of the part treated which was magnetic with the different current-strengths indicated; column 2, the percentage of the total sample which was magnetic under the same conditions (*e. g.*, $90.11 \times 33.61 = 30.28$). The portion magnetic at $\frac{2}{16}$ ampere (about one-third of the total) still contained nearly 2 per cent. of Ni; so the loss was still very great, while the non-magnetic concentrate was not very greatly enriched.

All the products of these two experiments were then mixed, crushed to pass through 60-mesh and treated as shown in Table IX.

TABLE IX.—*Magnetic Separation of Mixed Sample Crushed to Pass No. 60 Mesh. Third Experiment.*

Product No.	Amperes.	Magnetic Portion.	Analyses.		
			Ni.	Cu.	Fe.
		Per Cent. of Total.	Per Cent.	Per Cent.	Per Cent.
1	$\frac{1}{8}$	44.26	1.69	0.13	55.50
2	$\frac{1}{4}$	41.96	2.16	0.18	54.80
3	$\frac{1}{2}$	0.37	2.16	0.26	50.30
4	$\frac{3}{4}$	0.37	4.19	0.70	32.50
5	1	0.49	5.29	0.93	24.55
6	2	1.13	8.96	0.97	20.85
7	3	1.38	13.55	0.76	21.55
8	4	3.95	10.29	0.46	22.35
9	5	4.19	12.71	0.60	19.60
10	6	0.89	4.17	3.18	12.65
11	28	0.77	1.53	14.36	19.65
12	tails	0.52	0.38	1.64	8.25

At $\frac{1}{8}$ ampere, 44.26 per cent. of the sample was magnetic, and the product contained 1.69 per cent. of Ni. At $\frac{1}{4}$ ampere, 86.22 per cent. was magnetic, and the product contained 1.92 per cent. of Ni. If the remainder, 13.78 per cent., were considered as the non-magnetic concentrate, we would have a comparatively rich nickel-ore, but the losses in the magnetic portion are so great that a commercial separation by this method is out of the question. All the other experiments led to the same conclusion. Intermediate products, rich in nickel, were easily obtained; but in no case was the nickel in the magnetic portion reduced to such an extent that it could be economically rejected.

D. P. Shuler, Sudbury, Ont., has recently (1902) taken out patents for a process whereby he proposes to eliminate the

copper from the nickel-iron portion by magnetic concentration, and subsequently to convert the latter, after roasting, into a nickeliferous pig-iron. The copper-nickel concentrate will, of course, be treated separately for its metallic content. This seems to be the most fruitful field for investigation now open in this connection, and about the only method of treatment which promises to yield results capable of industrial application.

The Nickel-Bearing Mineral.[17]—Prof. S. L. Penfield[18] first definitely proved the existence of pentlandite in the ores from the Sudbury nickel-copper mines. Later, David H. Browne[19] showed that pentlandite was the principal nickel-bearing mineral. On the assumption that the ores were the result of a magmatic segregation from an original fused magma, he tried to show that the coarser the grain of the pyrrhotite, and the deeper it lies below the surface, the more nickel exists as pentlandite. On the other hand, the finer-grained the ore, and the more rapidly it has cooled from the fused state (*i. e.*, the nearer it is to the surface), the more nickel exists as an element replacing the iron in the pyrrhotite. As will appear later in this paper, however, this relation does not hold good.

In order to determine as nearly as possible how much of the nickel occurs as a separate mineral, and how much, if any, replaces iron, and also to ascertain the composition of the nickel-mineral, several series of experiments were made by the writer.

First Series of Experiments.—A number of representative samples of pyrrhotite were ground to pass through 100-mesh and the non-magnetic portion was removed as completely as possible by repeated treatment with a small horse-shoe magnet. The nickel-contents of the original samples are given in column I., and those of the magnetic concentrate in column II., Table X. The nickel is seen to have been materially reduced, and the results seemed to indicate a pretty constant quantity remaining with the magnetic part. Further experiments, however, showed that this was purely an accidental relation.

Second Series of Experiments.—The original samples were coarsely crushed and the magnetic portion was sized between

[17] A preliminary note on this subject was published in the *Engineering and Mining Journal*, vol. lxxiii., No. 19, p. 660 (May 10, 1902), by the writer.

[18] *American Journal of Science*, Third Series, vol. xlv., No. 270, p. 493 (June, 1893).

[19] *Engineering and Mining Journal*, vol. lvi., No. 23, p. 565 (Dec. 2, 1893), and *School of Mines Quarterly*, vol. xvi., No. 4, p. 297 (July, 1895).

40- and 60-mesh, then freed as well as possible from non-magnetic material, crushed between 60- and 80-mesh and again concentrated. By successive treatments the mineral was finally reduced to a fine powder. The ultimate product was then assayed for nickel. As shown in column III., Table X., the nickel was much reduced, but not entirely eliminated.

Third Series of Experiments.—To see if it were possible to still further reduce the nickel-content, a number of samples were very carefully prepared. They were coarsely crushed and the purest mineral selected. This was crushed to pass through 10- on 20-mesh, and the finer material was rejected. All the non-magnetic portion was eliminated and the concentrate was then crushed to 20- on 40-mesh, the finer part being again rejected. The operations were repeated until the ore was finally ground in an agate mortar, the non-magnetic part being very carefully removed each time. The nickel in the final concentrate is given in column IV., Table X.

TABLE X.—*Experiments in the Magnetic Concentration of Nickeliferous Pyrrhotite.*

Location.	I. Ni.[a]	II. Ni.	III. Ni.	IV. Ni.	
	Per Cent.	Per Cent.	Per Cent.	Per Cent.	
1. Elsie mine	2.44	2.22	0.98	.....	Fine-grained pyrrhotite.
2. Stobie mine	3.05	2.14	0.68	.....	Fine-grained pyrrhotite.
3. Frood mine	2.40	2.07	1.05	0.65	Coarse-grained pyrrhotite.
4. Mount Nickel mine	3.06	2.14	0.75	0.70	Medium-grained pyrrhotite.
5. Copper Cliff, No. 2 mine.	4.00	2.00	0.70	.....	Coarse-grained pyrrhotite.
6. Copper Cliff, No. 4 mine.	3.30	2.32	0.83	.....	Coarse-grained pyrrhotite.
7. Creighton mine (a)	2.32	2.25	1.20	0.70	Coarse-grained pyrrhotite.
Creighton mine (b)	4.15	.....	.....	0.45	Fine-grained pyrrhotite.
8 Gertrude mine	4.00	2.30	1.10	.....	Massive pyrrhotite.
9. Victoria mine	3.40	2.46	0.80	.....	Fine-grained pyrrhotite.

[a] Nickel with a trace of cobalt.

The results show conclusively that the nickel present is not replacing part of the iron in the pyrrhotite, but exists as a separate mineral. The fact that all the nickel could not be eliminated by the methods used does not indicate that even the amount that remained was an essential part of the pyrrhotite, as several factors enter which render its complete removal practically impossible. In the first place, the nickel-mineral is very intimately associated with the magnetic pyrites; and even a minute adhering fragment of the latter will cause it to

be carried over with the magnetic portion. It is also to be noted that the nickel-mineral itself is slightly magnetic, and in the form of a powder is attracted by even a small magnet.

As a result of these experiments I feel justified in saying that all the nickel, in the Sudbury ores at least, occurs as a separate mineral, and that in this district there does not exist a true nickeliferous pyrrhotite, in the sense that the nickel isomorphously replaces part of the iron in that mineral.

Experiments on Swedish and Norwegian ores of a similar nature show that a large part of the nickel can be eliminated by magnetic concentration; and taking these results, in connection with the foregoing, it is pertinent to ask, "Is there such a thing as a true nickeliferous pyrrhotite?"

The results show that even with the most careful treatment, a commercial separation of the nickel by magnetic concentration is prohibited by the considerable loss of nickel involved.

The Non-Magnetic Residue.[20]—Analyses of the non-magnetic residues, roughly freed from impurities, were made to get an idea of their compositions.

The small amount of copper was estimated as chalcopyrite, and the necessary amounts of iron and sulphur deducted. The ratios of Fe : Ni : S (taken as 1) were then calculated, and the results are given in Table XI.

TABLE XI.—*Analyses of the Non-Magnetic Residue from Pyrrhotites.*[a]

Location.	Cu.	Total Fe.	Total S.	Ni.	Co	Fe.[b]	S.[b]	Ratios. (S = 1.00.)		
								S.	Ni + Co.	Fe.
	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.			
1. Victoria mine	0.95	28.50	31.92	31.65	0.65	27.66	30.96	1.00	0.570	0.514
2. Frood mine	0.84	29.36	32.85	32.25	0.84	28.65	32.04	1.00	0.565	0.512
3. Creighton mine	1.20	29.50	34.25	33.00		28.45	32.80	1.00	0.550	0.50
4. General sample	0.80	27.11	30.30	29.71	0.60	26.40	29.46	1.00	0.565	0.515
5. Copper Cliff mine[c]	0	.....	.....	35.05		29.80	34.35	1.00	0.56	0.50
6. Copper Cliff mine[c]	0	.....	.....	35.00		30.30	33.50	1.00	0.571	0.52
7. Evans mine	0	.....	.....	34.90		29.60	33.35	1.00	0.571	0.51
8. Stobie mine	0	.....	.....	34.70		29.90	33.90	1.00	0.56	0.505

[a] For the sake of uniformity the following revised atomic weights are used throughout: Ni, 58.69; Co, 58.99; Fe, 56.02; S, 32.07.

[b] After deducting the necessary amounts to form chalcopyrite with the copper present.

[c] Analyses by D. H. Browne; Nos. 5 and 8 contained some pyrrhotite; Nos. 6 and 7 were purer. *Engineering and Mining Journal*, vol. lvi., No. 23, p. 565 (Dec. 2, 1893).

[20] The residue is spoken of for convenience as being non-magnetic, although in reality slightly so.

The striking uniformity of the ratios obtained at once indicated the similarity of the mineral in all these cases; and further work on carefully-purified material confirms this view.

The pyrrhotite from the Creighton, Worthington, and Frood mines shows considerable amounts of the non-magnetic material, in pieces up to 0.75 in. in diameter, fairly pure, and specimens from these localities were chosen as affording the best material to work on.

The ore was first roughly crushed and the pyrrhotite removed by a magnet. The larger non-magnetic fragments were taken and picked over under a lens, carefully discarding any that was even suspected of containing pyrrhotite.

The samples were then crushed successively to pass through No. 20, No. 40, No. 60, No. 80, and No. 100 mesh, each time discarding the fines and going over them with a magnet, examining under a lens, and removing all foreign material till they were too fine to treat in this way. They were finally ground in an agate mortar and again gone over with a weak magnet, which attracted the mineral but little and served to remove any traces of pyrrhotite that might remain. In this way the samples were obtained as pure as it is practically possible to get them, and they were ready for analysis; the results are shown in Table XII.

TABLE XII.—*Analyses of Nickel-Bearing Mineral.*[a]

Location.	Cu.	Ni.	Co.	Fe.	S.	Ratios. (S = 1.00.)		
						S.	Ni + Co.	Fe.
	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.			
1. Creighton.....	0	34.82	0.84	30.00	32.90	1.00	0.589	0.518
2. Worthington...	0	33.70	0.78	29.17	32.30	1.00	0.583	0.517
3. Frood.....	0	34.98	0.85	30.04	33.30	1.00	0.588	0.513
4. Copper Cliff[b].	0	34.23	0.85	30.25	33.42	1.00	0.573	0.518

[a] The small amount of residue consisted of siliceous gangue. These analyses were made in the laboratory of the School of Mining, Kingston, Ont., which was kindly placed at the writer's disposal.

[b] Penfield, *American Journal of Science*, Third Series, vol. xlv., No. 270, p. 493 (June, 1893).

The composition of the non-magnetic residue at once suggests pentlandite, and as such Penfield describes the sample he examined (No. 4 in Table XII.).

The pentlandite from Lillehammer, Norway, corresponds very closely to it in physical properties, but carries a lower percentage of nickel (20 to 22 per cent.)

The Sudbury mineral occurs, in part, finely disseminated through the pyrrhotite, so that it cannot be detected, even with the aid of a lens, and partly in larger grains and segregations, at times an inch in diameter. Usually it possesses the characteristic platy structure and octahedral parting, though this is at times obscured. On fresh fracture, the mineral has a light steel-gray or silver-white color, which soon changes on exposure to the peculiar and characteristic light bronze-yellow. When fresh and massive it is with difficulty to be distinguished from the fresh pyrrhotite, but on a slight superficial oxidation the difference becomes quite pronounced.

The Lillehammer pentlandite has a ratio of FeS : NiS of about 2 : 1, and its formula is given as 2FeS + NiS. Penfield[21] gives the ratio of the Sudbury mineral as (Fe + Ni) : S = 1 : 1, or (Fe + Ni) S.[22] By a reference to Table XII. it will be seen that the ratio (Fe + Ni) : S is (1) 11.07 : 10; (2) 11 : 10; (3) 11.03 : 10; and (4) 10.91 : 10; that is, there is an excess of the metallic constituents over the amount required by the formula (Fe + Ni)S. The same excess is indicated in the analyses of less pure material given in Table XI. This relation is constant and cannot be regarded as accidental, especially since the analyses of the purest samples from different localities show the ratio to be constant at 11 : 10. Just what this peculiarity signifies it is difficult to say; but it seems to indicate that the structure of the pentlandite molecule is more complicated than that represented by (Fe + Ni)S, even though it is advantageous to represent minerals by the simplest possible formulas.

An excess of sulphur over the metal is by no means uncommon in minerals (*e.g.*, in pyrrhotite, polydymite, beyrichite, etc.); but an excess of metallic contents seem unique.

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[21] *Loc. cit.* The analysis given by Professor Penfield, in this paper, agrees almost exactly with those made by the writer, but by a slight error in calculation, his analysis worked out exactly to the formula (Fe + Ni)S, instead of showing an excess of metallic constituents, as is actually the case; that is, the ratio of (Fe + Ni) : S in the material examined by Professor Penfield is almost 11 : 10, instead of 1 : 1 as given.

[22] Nickel and cobalt being taken together.

Such a formula as $(Fe + Ni)_{11}S_{10}$ is not convenient; but it appears to be the only means of expressing the results of analysis.

Another interesting feature is the ratio of nickel to iron, which is quite constantly also nearly 11 : 10, while that of nickel to cobalt is about 42 : 1.

An intimate mixture of some sub-sulphide with what might be regarded as normal pentlandite [(Ni + Fe)S] is, of course, a possibility; but if this is the case it must be in a definite and constant ratio, as the mineral shows the same phenomenon throughout the whole district.

But this is a mere speculation. There is no direct evidence on which to base the assumption, and at present it seems most reasonable to imagine a peculiar molecular arrangement of the atoms of the mineral itself. As the matter now stands, however, the relations are unexplained, and must be the subject of further investigation before a satisfactory conclusion is reached.

The Formula of the Pyrrhotite.

A large number of the magnetically-separated samples were analyzed, in an attempt to determine the formula of the pyrrhotite, and with a fair amount of success. A number of factors had to be taken into consideration, and tended to render the results in some cases rather unsatisfactory, so that absolute uniformity was not attained.

The nickel present was calculated to pentlandite on the basis of the ratios given above, and the necessary amounts of iron and sulphur were deducted. As there was a persistent, though varying, amount of magnetite in all the samples, it was necessary to determine this. The estimation of the oxide (Fe_3O_4) in the presence of the magnetic sulphide presented considerable difficulty, and this is probably the main cause of the discrepancies.

After a number of experiments, it was found that by treating the sample with a dilute (10 per cent.) solution of nitric acid, the pyrrhotite could be largely removed, while the magnetite was but little affected. The separated sulphur was removed by means of bromine and carbon bisulphide; and after several treatments the residue of magnetite was obtained pure, and the iron was estimated by titration. The nature of the various

operations involves the possibility of some loss, especially as the amount of magnetite is comparatively small; but, on the whole, the method answered very well. The great majority of the analyses indicated that the pyrrhotite could be represented by the formula Fe_8S_9, while two or three worked out to Fe_7S_8 and Fe_9S_{10}; so that the former can be regarded as the most probable for the pyrrhotite from the Sudbury district.

For purposes of comparison, a number of pyrrhotites, as pure as it was possible to obtain them, from various localities, were further purified by magnetic concentration and analyzed. One from Rossland, B. C., conformed to Fe_8S_9, one from Anthony's Nose, N. Y., to Fe_7S_8, as did also a sample from Enterprise, Ont.[23]

As absolute uniformity, even in the material from a limited district, was not obtained, it would not be wise to draw general conclusions, or attempt to make any general applications, without an exhaustive study of more representative material.

It seems, however, a justifiable conclusion from the work so far that the pyrrhotite from the nickel-region of Sudbury is of fairly-uniform composition, and is best represented by the formula Fe_8S_9.

Summary.

In recapitulation, the main facts may be summed up briefly as follows:

1. Our present conception of the constitution of pyrrhotite is very unsatisfactory. The nature and associations of the mineral are such that analyses are often misleading, and a great deal of careful, systematic work is necessary as a basis for generalizations of any value.

2. The conditions under which pyrrhotite is formed in nature are still very little understood.

3. Nickel is universally associated with pyrrhotite in greater or less amount, though in but few instances is it present in quantities of economic importance.

4. The Sudbury pyrrhotites are very uniform over large areas, as to metallic contents and associated minerals.

5. Aside from the copper- and nickel-minerals, the others

[23] This pyrrhotite is associated with a remarkable deposit of molybdenite, which has recently been exploited.

are of small economic importance, except, perhaps, sperrylite, which is furnishing an increasing amount of the world's supply of platinum.

6. The magnetic separation of the nickel from pyrrhotite is out of the question commercially.

7. The nickel occurs in the pyrrhotite as the so-called pentlandite, and not as an essential constituent of this mineral.

8. Nearly all the pentlandite can be separated from the pyrrhotite by magnetic methods; but peculiar physical conditions seem to render its absolute elimination an impossibility.

9. The pentlandite does not conform to the generally-accepted formula (Fe + Ni)S. The metallic constituents are always in excess of the sulphur by a constant ratio of 11 : 10. But, as yet, no satisfactory explanation of this phenomenon can be advanced.

10. The pyrrhotite from Sudbury can best be represented by the formula Fe_8S_9.

11. Pyrrhotite and magnetite can be separated by a 10-per cent. solution of nitric acid with fairly-satisfactory results.

II. Genesis of the Sudbury Ores.

General Considerations.

For convenience, pyrrhotites may be divided into two main classes, according to their geological relations.

1. Those of the first class occur, often with more or less pyrite and chalcopyrite, as lenses in acidic gneisses and schists. These lenticular masses generally conform to the foliation of the schists, and are often repeated and connected by leaner zones, like *fahlbands*. Such deposits are of world-wide distribution; and, wherever found, generally carry pyrrhotite low in nickel, seldom containing more than 0.5 and usually less than 0.25 per cent.

2. The second class also is widely distributed. The deposits are likewise lenticular in shape, but they are associated with basic igneous rocks, usually of the gabbro type, or their metamorphic equivalents. Another characteristic feature is, that while they lie well within the limits of the eruptive rock, they generally occur at or near its contact with other rocks, such as granite, mica-schist, porphyry, or diabase. The pyrrhotite is

always associated with more or less chalcopyrite and pyrite, and at times with the rarer minerals, pentlandite, sperrylite, and gersdorffite. The characteristic minerals of the basic rock are also intimately mixed through the prevailing sulphides. Nickel is almost invariably present, at times reaching the amount of 10 per cent. Generally, however, from 2 to 4 per cent., as at Sudbury, would be a fair average. In Norway and Sweden the average is lower.

It should be added that the above general statements as to the nickel-contents of the two classes of pyrrhotite-deposits is subject to some important exceptions.

3. Outside of these two classes, pyrrhotite is found at times in considerable quantity in true fissure-veins; but this occurrence is relatively unimportant.

Types of the first class, as represented by the Phillips mine, at Anthony's Nose, N. Y., the Ducktown, Tenn., deposits, and numerous *fahlbands* in various parts of Ontario, Norway, and Sweden, are believed to be replacement-deposits along crushed zones.

To the second class of deposits an igneous origin has been attributed in recent years by some of the ablest workers in this field of geology. The sulphides are regarded as original rock-constituents, and it is thought that, being among the first minerals to crystallize in a cooling rock-magma, they became concentrated in their present position before the rock solidified.

It is well established that rock-magmas—especially the more basic—tend to divide into fractional parts of varying acidity. What forces produce this "magmatic differentiation" is not clearly understood.

There seems to be excellent evidence to prove that many deposits of magnetite (always titaniferous), chromite, and corundum have originated in this way. That is, they are simply excessively basic developments of magma, in which the mineral in question is a normal, or common, accessory constituent.

These deposits, however, consist of oxidized compounds; and their segregation presents fewer theoretical difficulties than does that of the sulphides.

Value of the Classification.—Quite apart, however, from theories of origin, the distinction above made as to geological relations is of the utmost importance from an economic standpoint.

This view of the relative value of the pyrrhotites in acid and basic rocks, as nickel-ores, is strongly urged by Professors Adams and Kemp in valuable papers which appeared about the same time.[24]

The Sudbury Pyrrhotite-Deposits.

In studying the origin of pyrrhotite of the second class, particular attention has been paid to the Sudbury deposits. Reference will, however, be made to similar deposits elsewhere when necessary.

Before proceeding with the consideration of the origin of the ores, it will be necessary to give a brief account of the geology of the deposits, especially as the ideas formerly held have been recently much modified. The Canadian Geological Survey has lately paid particular attention to the district, and it is now recognized that its relations are much more complex than was at first thought. In his preliminary report on the district, Dr. A. E. Barlow,[25] who has had charge of the work, gave some general ideas of the nature of the rocks and the extent of the ore-bodies. But the field-work was not completed at the time, and many new facts have been collected during the past season; hence, his final views on the subject will not be presented until the full report is issued. Meanwhile, the question must be considered with the understanding that some of the previously-presented conceptions are subject to revision.

The deposits are prevailingly lenticular, pinching out in both directions and conforming to the general strike of the inclosing Huronian strata. The ore always occurs in, and contains fragments of, a basic and altered eruptive of the gabbro type.

The ore-bodies may occur either well within this eruptive or at its contact with the other prevailing rocks of the district, namely, granite or granite-gneiss, quartzite, or the metamorphosed representative of a series of basic sedimentaries, now termed "greenstones" by the Survey.

Dr. Barlow says his investigations prove that the normal

[24] F. D. Adams, Preliminary Report on the Geology of a Portion of Central Ontario, *Annual Report of the Geological Survey of Canada*, vol. vi., Report J (1892–93). On the Igneous Origin of Certain Ore-Deposits, *Journal of the General Mining Association of the Province of Quebec*, vol. ii., pp. 35 to 53 (1894–95). J. F. Kemp, The Nickel-Mine at Lancaster Gap, *Trans.*, xxiv., 620 (1894).

[25] *Summary Report of the Geological Survey Department of Canada* (1901).

or type-rock associated with the deposits is a member of the gabbro family of rather exceptional character. It nearly always has traces of a broad, ophitic structure,[26] and the presence of hypersthene or enstatite justifies its classification as a norite. Considerable original quartz is, at times, present. In general, the rock consists of a basic plagioclase, hypersthene, or enstatite, augite, biotite, hornblende, and quartz, with smaller quantities of accessories. Associated with the nickel-bearing norite and grading into it, is a rock which is called "micro-pegmatite." Microscopically studied, the change consists in the gradual assumption of a reddish color and an increase in quartz and feldspar. The hornblende is replaced by biotite and the plagioclase by orthoclase.

The Nickel-Belts.—Three main belts of these norites and associated micro-pegmatites are now recognized, designated as the northern, middle, and southern belts, respectively. They are, at present, mapped as separate, but genetically and mineralogically they are essentially identical. The northern belt runs from the old Ross mine (Foy township) ESE. to Bowell, where it branches. The limits of the smaller branch have not been ascertained, but the larger trends to the north and connects with the large area of basic rocks to the west of Lake Wahnipitae. The middle band begins in Levack township to the southwest of the northern, and runs in a southwesterly direction across Windy lake to Trill.

The southern and most important belt begins in scattered patches in Drury township (south of Trill), which unite and extend unbrokenly NE. for over 32 miles into Denison township, where a maximum width of over 4 miles is attained. Here it is divided into two by an intrusion of coarse "augen" granite-gneiss. The northern, or more important, branch pursues a northeasterly direction through Garson township (south of Lake Wahnipitae). The southern branch crosses the Vermilion river and passes through Copper Cliff, where it rejoins the other.

It will thus be seen that the norite belt forms a sort of rough and somewhat disconnected ellipse, the center of which is occupied by the basin of later silicified volcanic tuffs, and surrounded by the so-called Laurentian acidic gneisses.

[26] This was found by the writer, also, to hold true as a general rule.

The unraveling of the complex, which was formerly included under the general name of "greenstone," has proved a very difficult problem. The results seem to show that it can be broken up into several series, comprising eruptives, metamorphosed sediments, and some as to whose true nature it is difficult to decide.

The relation of the granite intrusions also presents a difficult problem. These granites in many places, undoubtedly, cut some of the basic rocks in close proximity to the ore-bodies, but in other places they seem to be earlier than these.

The geologists of the Canadian Survey are now of the opinion that these granite rocks are intruded into rocks, largely of sedimentary origin, and classed as greenstones, but that these intrusions are earlier than the ore-bearing norite. The problem is complicated by the close similarity in mineralogical and chemical composition of the so-called altered sediments and the basic eruptives, and by the excessive metamorphism which all have undergone.

The points at issue are probably not yet finally settled, and a great deal of careful work will, no doubt, be necessary before the last word is spoken. In the absence of the full Survey report, the matter is in a very unsatisfactory state, but we may confidently expect, in Dr. Barlow's final utterance, a contribution of great scientific and practical value, shedding much light on the question.

Various Theories of the Origin of Nickeliferous Pyrrhotite.

A brief statement of the views held hitherto by prominent workers in this field is appropriate here.

Dr. Bell[27] brings out the following points:

1. That this area was the seat of volcanic activity, with explosive violence on a large scale.

2. The greenstones along certain lines hold an abundance of angular fragments of other rocks, especially quartzite, and this brecciated condition appears to be favorable to the accumulation of ore. (Blezard, Stobie, Copper Cliff, etc.) In fact, the ore-masses always consist of a breccia, of sulphides and country-rock in angular and rounded fragments of all sizes.

[27] *Annual Report of the Geological Survey of Canada*, vol. v., Report F (1890–91).

3. The ore-bodies are lenticular and parallel to the strike of the inclosing rocks.

4. The chalcopyrite in large masses is generally nearly pure, but the pyrrhotite is always mixed with a certain amount of stony matter. This may indicate that the former has segregated from the original mixture by some secondary process.

5. The chalcopyrite is often in the form of branching strings and partly surrounds stony inclusions. In some of the brecciated ore-deposits in Levack township, the spaces between the greenstone fragments are filled, partly with sulphides and partly with light-colored crystalline granite vein-matter.

6. The intimate association with the greenstone appears to indicate that they have originated first from a state of fusion, but have been more or less modified by other agencies. The presence of crystals of feldspar, quartz, apatite, etc., together with laminated iron pyrites and galena, indicates the action of solutions.

7. Both clastics and eruptives have suffered extensive metamorphism.

Von Foullon[28] also calls attention to the metamorphosed and brecciated condition of the diorite (more properly norite, or altered gabbro; Bell's greenstone) and to the fact that this appears to be the most favorable place for ore-deposits. Along a line of fracture which can be traced from the Dominion (Blezard) mine to the Vermilion, very similar deposits prevail, so it must be considered that the fracture caused them. There is also a fracture-line from the Copper Cliff to the McConnell mine in Denison township, along which ore outcrops, accompanied by diorite and a breccia of gneiss and quartz-syenite. He then adds that the ores are not deposited from solution, but are of igneous origin, because they occur in an eruptive rock.

Dr. F. D. Adams,[29] speaking of The Igneous Origin of Certain Ore-Deposits, claims such an origin for both the Sudbury and Norwegian pyrrhotites in gabbro. He thinks the ores segregated according to Soret's principle, and the formation of the minerals was determined according to Fournet's series.

[28] *Jahrbuch der kaiserlich-königlichen geologischen Reichsanstalt*, vol. xlii. (1892).

[29] *Canadian Mining Review*, vol. xiii., No. 1, p. 8 (Jan., 1894).

Philip Argall[30] also points out the faulted nature of the district. He considers that a leaching-out of the nickel and copper from the greenstones in which they were originally formed, and a concentration and precipitation along favorable zones, is a more reasonable explanation than that of magmatic differentiation.

E. Renshaw Bush[31] says, the schists in Denison and Graham townships in the vicinity of the nickel-bearing greenstones carry pyrrhotite in grains and aggregates between the layers. He suggests the aqueous origin of the ores for the following reasons:

1. Because of the tendency of the sulphides to occur along planes of contact and fracture, and the impregnation of the rock near such planes.

2. Because the ore-bodies occur at the contact between structurally-different rocks.

3. Because of the impregnation of the schistose areas near the greenstones.

Merritt[32] thinks that a secondary concentration is necessary to explain certain features of the ore-bodies, viz.: the presence of native copper; the "horses" of barren country-rock, cemented by ore; the "fluccan" observed across certain deposits; and the sharply-brecciated nature of some of the "horses."

D. H. Browne,[33] in an article on Segregation in Ores and Mattes, seeks to draw an analogy between a pot of matte, in which he found that the nickel and copper sulphides tended to separate somewhat, and the Sudbury ore-bodies, where it is seen that pyrrhotite and chalcopyrite, to a certain extent, form separate masses.

Prof. J. F. Kemp[34] appeals to the laws of thermo-chemistry to explain the Sudbury deposits. As is well known, in a fused mass or solution the order of formation of compounds is determined by the amount of energy (heat) which they develop

[30] *Proceedings of the Colorado Scientific Society*, vol. iv., p. 395 (1891–93).

[31] The Sudbury Nickel-Region, *Engineering and Mining Journal*, vol. lvii., No. 11, p. 245 (Mar. 17, 1894).

[32] *Trans.*, vols. xvii., 293 (1888–89), and xxiv., 755 (1894).

[33] *School of Mines Quarterly*, vol. xvi., No. 4, p. 297 (July, 1895).

[34] An Outline of the Views Held To-day on the Origin of Ores, *Mineral Industry*, vol. iv., p. 755 (1895).

on crystallizing. If, now, the gabbro magma is considered as an intrusion in which the bases have been concentrated near the walls by Soret's or some other principle, and a stream of sulphuretted hydrogen and sulphurous anhydride gases finds a way of escape along the contact, the sulphides would form in the order indicated above. This should give, in order, the sulphides of iron, copper, and nickel. Professor Kemp, however, recognizes that in this case nickel should be associated with the copper, not the iron sulphide.

Professor Vogt's views on this subject are well known.[35] He considers that on account of the close chemical and mineralogical relations of these deposits the world over, they can be explained only by a common general chemical process. He also emphasizes the fact that there is a regular transition from the pure ore, on the one hand, to normal rock, on the other, by a gradual decrease of sulphides. He claims further support for his theory in the facts that titaniferous magnetite is often present in the ore; that the platinum-metals, which are regarded as essentially of igneous origin, are found in Sudbury; and that eruptive magmas can dissolve considerable quantities of sulphides. The last seems to be shown by the fact that basic blast-furnace slags often contain from 3 to 5 per cent. of CaS and MnS; from 4 to 6 per cent. of FeS; and from 6 to 8 per cent. of ZnS, etc. His conclusion is that the sulphides are undoubtedly derived from original eruptive magmas by a process of differentiation according to Soret's principle, influenced by other factors, of which gravity may be important.

T. L. Walker[36] says that near the nickel-deposits the basic eruptives are more or less completely altered by metamorphism, while farther away the change is less, till practically unaltered rock is found. He also brings out the very important fact that some at least of the granites, in contact with the nickel-bearing greenstones, formerly held to be of Laurentian age, are really younger than the greenstones. This is well seen at the Murray mine, where the "younger granite" sends apophyses into the surrounding greenstones.

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[35] Sulphidische Ausscheidungen von Nickelsulphiderzen. *Zeitschrift für praktische Geology*, vol. i., No. 4, p. 125 (Apr., 1893).

[36] Geological and Petrographical Studies of the Sudbury Nickel District. *Quarterly Journal of the Geological Society*, vol. liii., No. 209, p. 40 (Feb., 1897).

Breccias are also formed in places by the inclusion of angular fragments of greenstone in the granite. Similar examples are seen in the granites south of the Blezard mine and the coarse-grained gneiss north of the Copper Cliff, which is essentially the same rock.

In direct opposition to the views of Professor Vogt, another eminent European geologist, Prof. R. Beck[37] (Freiberg), may be quoted. Professor Beck in his admirable work on ore-deposits (Fig. 18) pictures a polished section of mixed ore and rock from the Murray mine, near Sudbury, showing its brecciated nature. Such an association, he claims, could not result from a direct magmatic segregation, but must have been due to a separation of the ore, *during* or *after* the metamorphism.

Speaking of the Norwegian nickel-deposits, Professor Beck says there are weighty considerations opposed to the theory of a direct igneous origin of the ores.

1. On physical grounds it is very difficult to understand how the molten sulphides penetrated so far into the cool, surrounding rocks (schists) as Vogt figures it.

2. On the basis of a microscopical examination of the ore, he considers that the corrosion of the residue of the rock-minerals in the ore is due to solution by water, especially as most of the ore occurs in very strongly metamorphosed parts of the gabbro, and that here the ore-separation appears later than the metamorphism. In Figs. 16 and 17[38] the relations are shown. The gabbro and norite, associated with the ore, is nearly always changed to amphibolite, or garnet-amphibolite, and the ore seems to have followed the metamorphic changes, or in some cases to have been contemporaneous with them. The conclusion is that the important concentration of the ore took place *during* the regional metamorphism, and *later* by the aqueous method.

Posepny,[39] referring to the Sudbury ore-bodies, claims that an igneous origin is a "chemical impossibility." But the contention is not borne out, when we consider that pyrrhotite is one of the commonest of the early crystallizations from the gabbro magma.

[37] *Lehre von den Erzlagerstätten* (1901).

[38] *Op. cit.*, pp. 41 and 42.

[39] *The Genesis of Ore-Deposits*, p. 146 (1902).

S. F. Emmons[40] is of the opinion that the ore has been concentrated by percolating waters along lines of faulting and brecciation.

The Rossland Pyrrhotite-Deposits.

By way of comparison, a word about the Rossland, B. C., pyrrhotites may not be out of place. The writer has to thank R. W. Brock, of the Geological Survey of Canada, who has been one of the chief workers in this province, for the latest data.

The ore-bodies here, while not carrying nickel in any quantity, have the same general associations as at Sudbury; and it is now fully established that they are of secondary aqueous origin.

During the trial of the suit of the Iron Mask Mining Co. against the Centre Star Co., in 1899, evidence was submitted by Messrs. Clarence King, Waldemar Lindgren, and R. W. Raymond as to the nature of these deposits.[41]

Stated briefly, the Rossland district forms part of a huge system, reaching from Cape Horn to the Arctic, and has been involved in the enormous dynamic and volcanic effects which this region has undergone from early geological times. Following the folding of the dynamic periods, the deposition of mineral matter in the fissures and along lines of weakness took place. In connection with most of the ore-bodies three types of rocks are represented.

1. A monzonite, often carrying pyrrhotite, and with the original structure more or less obliterated.

2. A darker, coarser-grained rock of the gabbro family, consisting of augite and triclinic feldspar, with little or no orthoclase.

3. The third is composed largely of hornblende and orthoclase.

These types are doubtless local variations of the same magma, but of successive flows.

The veins are considered as distinctly of the fissure-type, and many of them are of the "shear-zone" variety—*i. e.*, consisting of a number of more or less parallel seams, with little displacement and no open fissures. The depth of the fissuring

[40] Geological Distribution of the Useful Metals in the United States, p. 65, this volume.

[41] *Records of the Supreme Court of British Columbia*, 1899.

FIG. 1.—MOUNT NICKEL MINE.

Photograph of polished section of ore. The light is chalcopyrite and pyrrhotite; the dark is gangue and rock. Slightly enlarged.

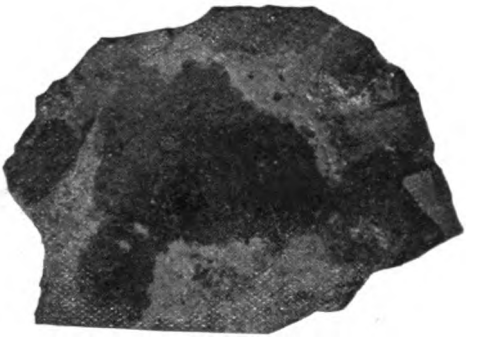

FIG. 2.—MOUNT NICKEL MINE.

Photograph of polished section of ore and rock, showing brecciated character. Slightly enlarged.

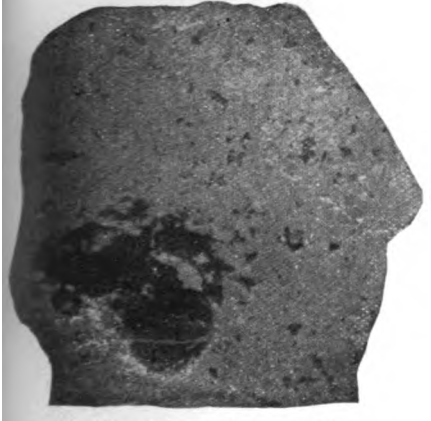

FIG. 3.—MOUNT NICKEL MINE.

Polished section of massive ore with unreplaced rock (dark). Pyrrhotite and chalcopyrite indistinguishable in the photograph. Slightly enlarged.

FIG. 4.—STOBIE MINE.

Photograph of polished section of ore (light), with angular and rounded rock-fragments (dark). Slightly enlarged.

FIG. 5.—MOUNT NICKEL MINE.

Photomicrograph of rock containing ore, showing the ore in parallel veinlets through the rock-minerals. The white is feldspar containing ore (dark), and granular and fibrous hornblende and hypersthene (shaded). Field, 2.5 mm.

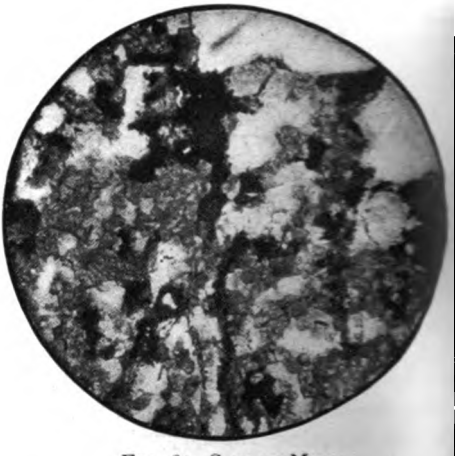

FIG. 6.—STOBIE MINE.

Photomicrograph of ore-rock. The dark is ore in veinlets, etc. The white is feldspar, and the shaded is hypersthene, often with ore in the cleavages. Field, 2.5 mm.

FIG. 7.—MOUNT NICKEL MINE.

Drawn from blue-print of photomicrograph, showing the ore in veinlets through the rock-minerals. The dark is mostly pyrrhotite, the white is feldspar, and the shaded is hypersthene. Field, 2.5 mm.

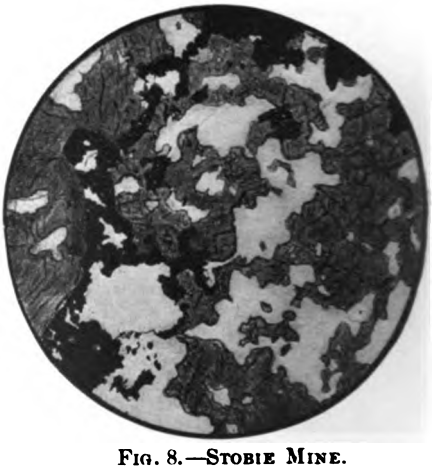

FIG. 8.—STOBIE MINE.

Drawn from blue-print of photomicrograph, showing the ore (dark) sharply outlined against the fresh hypersthene (shaded) and feldspar (white), and entering the cleavages. Field, 2.5 mm.

FIG. 9.—ELSIE MINE.

Photograph of polished section of ore (light), showing the irregular, vein-like replacement of the rock (dark). Slightly enlarged.

FIG. 10.—COPPER CLIFF MINE.

Photograph of polished section of ore, showing the vein-like character of the sulphides. The pyrrhotite has been touched out with Chinese white to form a contrast with the chalcopyrite (dark). Slightly enlarged.

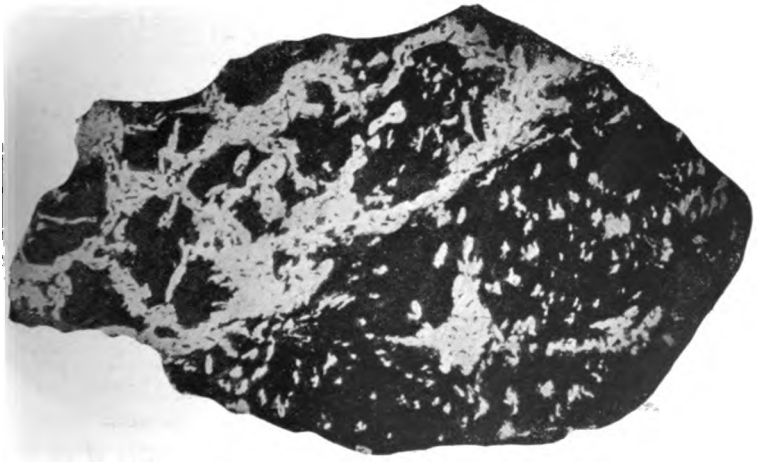

FIG. 11.—COPPER CLIFF, NO. 2, MINE.

Photograph of polished section of ore and rock, showing the brecciated character, and the vein-like nature of the ore (light), and the centers of unreplaced rock (dark). The sulphides are brought out by touching up with Chinese white. Slightly enlarged.

FIG. 12.—ELSIE MINE.

Photomicrograph of ore-rock, showing altered feldspar (white) with parallel veinlets of ore (dark) and irregular patches of pale-green hornblende (shaded). Field, 2.5 mm.

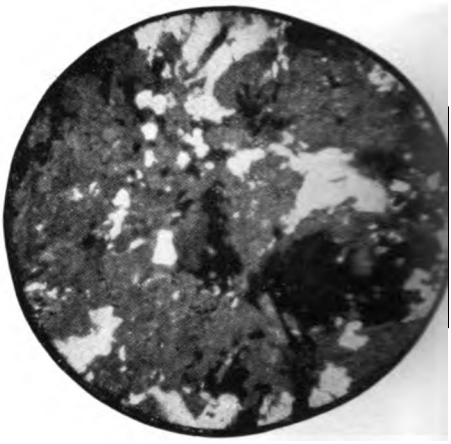

FIG. 13.—COPPER CLIFF, NO. 2, MINE.

Photomicrograph of ore-rock, showing ore (dark) replacing fibrous and granular hornblende (shaded), and entering cracks and cleavages. The white is feldspar and quartz. Field, 2.5 mm.

FIG. 14.—CREIGHTON MINE.

Drawn from blue-print of photomicrograph, showing the ore in veinlets, through altered hornblende, chlorite, and biotite (shaded). The white is feldspar and quartz. Field, 2.5 mm.

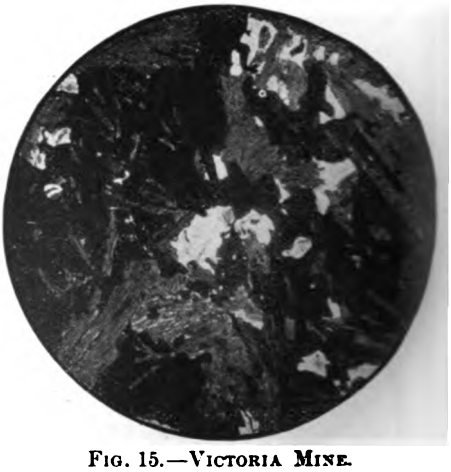

FIG. 15.—VICTORIA MINE.

Drawn from blue-print of photomicrograph, showing sulphides (dark) between and surrounding fibers of hornblende and biotite (shaded), and entering cleavages. The white is quartz and feldspar. Calcite is also present. Field, 2.5 mm.

FIG. 16.—GERTRUDE MINE.

Drawn from blue-print of photomicrograph, showing the sulphides (dark) parallel to the fibers of the hornblende (shaded). The white is feldspar. Field, 2.5 mm.

FIG. 17.—GERTRUDE MINE.

Drawn from blue-print of photomicrograph, showing sulphides (dark) parallel to the cleavages of the fibrous hornblende (shaded), and following the changes of direction. Field, 2.5 mm.

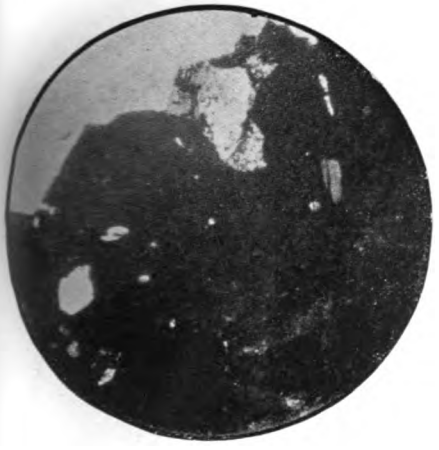

FIG. 18.—CREIGHTON MINE.

Photomicrograph of ore with small residues of hornblende, feldspar, and quartz, partly replaced. Field, 2.5 mm.

FIG. 19.—GERTRUDE MINE.

Photomicrograph of ore-rock, with ore (dark) replacing the hornblende and biotite (shaded) along cracks and cleavages. The white is feldspar and quartz. Field, 2.5 mm.

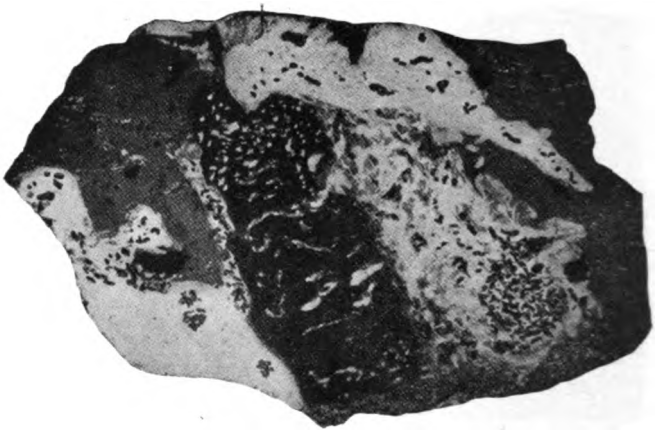

FIG. 20.—GERTRUDE MINE.

Photograph of polished section of ore, showing unreplaced rock (dark). The light is pyrrhotite and the shaded is chalcopyrite. Slightly enlarged.

FIG. 21.—CREIGHTON MINE.

Photograph of polished section of ore, showing the vein-like nature of the sulphides. The light is pyrrhotite and the dark is chalcopyrite. Slightly enlarged.

FIG. 22.—WORTHINGTON MINE.

Photograph of polished section of ore, showing irregular patches of unreplaced schistose rock. Slightly enlarged.

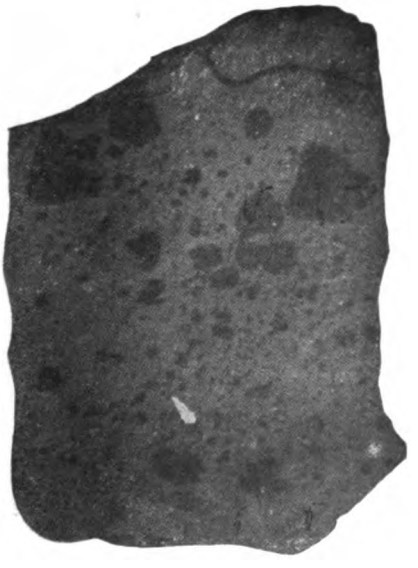

FIG. 23.—WORTHINGTON MINE.

Photograph of polished section of ore, showing round and angular fragments of unreplaced rock. Slightly enlarged.

FIG. 24.—COPPER CLIFF MINE.

Drawn from blue-print of photomicrographs, showing ore (dark) between the grains and fibers of the rock-minerals. Field, 2.5 mm.

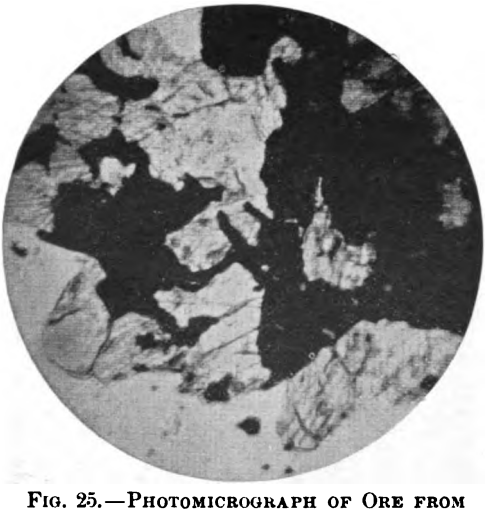

FIG. 25.—PHOTOMICROGRAPH OF ORE FROM THE EAST TENNESSEE MINE.

The white mineral is calcite. The dark mineral is chalcopyrite, which has entered cracks and fissures in the calcite. Magnified 40 diameters.

FIG. 26.—PHOTOMICROGRAPH OF ORE FROM THE EAST TENNESSEE MINE.

The white mineral is actinolite. The dark mineral is chalcopyrite, which has filled even minute cracks in the shattered actinolite and has replaced it when crushed and altered. Magnified 17.3 diameters.

permitted a circulation of deep-seated thermal waters and a deposition of the chemicals carried in solution along the lines of weakness by a decomposition and replacement of the rock-minerals. The final result is either: (1) a deposition of the ore on one plane or fissure of the "shear-zone," or (2) a replacement of the rock between two planes, or (3) the replacement of a whole zone, and so on with endless variations. The replacement of the rock-minerals by ore (largely chalcopyrite and pyrrhotite) took place molecule by molecule, producing what is really a pseudomorph. The replacement is well seen near the Iron Horse mine, where large diallages or augites have changed to ore, while the surrounding country-rock was only partly transformed.

The replacement has, at times, been so intense that an almost solid body of sulphides (with quartz and calcites) results. In other places the original rock, more or less modified and silicified, has been only partly replaced and impregnated with ore.

Messrs. King, Lindgren, and Raymond were practically unanimous in their interpretation of the phenomena of the district, which agrees very closely with that of the Canadian Geological Survey, though the more recent work shows that slight modifications of the rock relations are necessary.

Briefly, the geology and relative ages of the rocks of the mining-district are as follows: [42]

1. The oldest series represented is classed as the Kootenay volcanic group, consisting of augite-porphyrites, tuffs, ash-beds, etc., of Palæozoic age.

2. Next comes a granite or grano-diorite (Nelson granite), probably Jurassic.

3. The Rossland monzonite, probably post-Jurassic.

4. Conglomerate, probably Tertiary.

5. Alkali (Rossland) granite and syenite.

The ores may occur in any of the rocks older than the alkali granite. This granite, whose main development is outside the limit of the Trail Creek sheet, is probably a Tertiary eruptive, and its dikes have penetrated all through the Rossland district.

As it happens, the principal mineralization is in the augite-porphyrites and monzonite, probably on account of the fractur-

[42] See Trail Creek map (1897), and *Summary Reports* (1896–1900) *of the Geological Survey of Canada.*

ing and cutting of these rocks by dikes, together with their relative solubility. The chief factor controlling the location of the mineralization seems to have been the alkali-granite contact and its system of dikes, the eruption of which *immediately preceded the formation of the ore-bodies.* The deposits are found where the dikes are particularly abundant.

The monzonite is the chief center of mineralization, but it is not to be considered as a volcanic neck, with the augite porphyrites and tuffs as part of the cone. These latter are much older and are cut by the Nelson granite. The occurrence of the ore has no relationship to the contact of the monzonite, being found both *outside* and *inside* its boundaries and in the younger rocks.

While magmatic differentiation has gone on to some extent, the *sulphides are not the result of it*, as is proved definitely by the work of the Survey.

A peculiarity of the rocks in which the ore occurs is that, while sheared and fractured, they are not brecciated, the dynamic movement having doubtless taken place under an immense load.

With reference to the ore-bodies themselves, some interesting points are brought out. The ore replaces the country-rock, partly or completely, starting from some fissure or line of fissures and often fading out gradually, the only "wall" being a commercial (economic) boundary. It may end abruptly at a fissure, in some cases due to a slip, which brought an unmineralized face against the ore.

Deposits very similar to those in the eruptives are found in the conglomerate (No. 4), which cannot be regarded in any other way than as of secondary origin.

The marked similarity of the geological relations in Rossland and Sudbury helps to make clear some of the more obscure points in the latter district. As the conditions of metamorphism, however, were not identical, the dynamic movements have manifested themselves in different ways, and it is not surprising that there should be striking dissimilarities. This difference is seen in the characteristic structures of the ore-bodies in the two districts. In Rossland, the fissure or shear-zone type of vein is predominant, with little or no sign of brecciation. In Sudbury, on the other hand, where the dynamical move-

ments probably took place under a very small load, a brecciation from faulting on a large scale, and probably with considerable movement, is characteristic. This will be brought out more clearly in speaking of the individual deposits.

This brief review indicates the wide differences of existing opinion as to the origin of pyrrhotite and the various interpretations which have been put upon the same phenomena.

Microscopical Evidence of the Origin of the Ores.

The evidence on which the secondary nature of these ores is here advocated is mostly altogether different in character from that already presented. It consists in the relations between the ores and the rock-minerals, brought out by microscopical examination. As no investigation of this kind has been previously made, the results will be given in some detail. Material from all the principal mining-locations has been studied, in order to avoid laying too much stress on local phenomena and to emphasize the genetic similarity of all the deposits of the district. The character of the ore-bodies in a large way will also be briefly noted as throwing much light on the general nature of the deposits.

Sudbury District.—The following separate localities in this district will represent its character:

1. Mount Nickel Mine, Blezard Township.—The ore consists of pyrrhotite (both coarse- and fine-grained) and a smaller amount of chalcopyrite, through which occur masses of almost barren rock, varying in size from minute particles to large "boulders," or "horses." Near what is considered as the foot-wall, the chalcopyrite increases in amount and the proportion of barren rock is greater.

The deposit is a good example of what is best described as a "*breccia ore-body.*" Rounded and angular rock-fragments of all sizes, with sulphides as a cementing material, are everywhere a striking characteristic. Besides the brecciation as a whole, the rock is often broken and fractured, and little seams and veinlets of ore occur all through it in a very typical manner.

In some of the open-cuts the ore is seen to run in particular streaks or bands, and may end very abruptly against barren rock.

The brecciated character, as it is seen in a large way, is also faithfully reproduced in hand-specimens. Figs. 1, 2, and 3, from photographs of polished sections, show these features very well.

While brecciation is one of the most striking characteristics of the deposit, evidences of faulting and shearing are not wanting in the slickensided and schistose nature of some of the rocks. There are a number of clayey seams, and some of the samples are decidedly fibrous. Along certain of the lines of crushing the rock is partly brecciated and partly slickensided, and here the ore occurs in veinlets and as a cement for the rock-fragments.

Under the microscope, the rock associated with the ore is black and dense, and belongs to the gabbro family. Hypersthene in fresh idiomorphic grains is very abundant, while augite and diallage are in subordinate amount. The pyroxenes have, in part, been altered to green fibrous hornblende. The feldspar forms an irregular mosaic, among the grains of which are fragments of hypersthene.[43] Biotite and quartz are sparingly present.

The relations of the sulphides to the rock-minerals are well shown. Where the pyroxene is somewhat altered it becomes fibrous; and here the sulphides are best developed.

Chalcopyrite and pyrrhotite form numerous veinlets between the fibers and cleavages of the rock-minerals. In places, where not too massive, the sulphides reproduce very faithfully the fibrous structure of the hornblende, though little of this mineral may remain, so that really a pseudomorph results. In one place or another all stages of replacement can be seen, from a few dust-like particles of sulphides in the hornblende to complete replacement. Where the pyroxene is fresh, the sulphides are outlined sharply against its margin, and only enter cleavages. In this way grains of pyroxene are more or less completely isolated. Figs. 5 and 7 show veinlets of sulphides through the fibrous minerals.

The relations seem to indicate a crushed zone, in which the feldspar has yielded and formed a mosaic, and along which the solutions carrying the sulphides have acted; the greater the

[43] The rocks from all the localities examined show a more or less pronounced migration of the dark silicates, especially secondary hornblende, into the feldspar.

alteration of the rock, the more complete being its replacement.

2. Blezard (Dominion) Mine, Blezard Township.—The character of the deposit is very similar to that of the Mount Nickel, showing the same brecciation and shearing. Under the microscope, however, the rock shows a more advanced stage of alteration than that of Mount Nickel. The pyroxene has changed to greenish fibrous hornblende and chlorite, which, in some cases, makes up nearly the whole rock. The feldspar is largely labradorite, and often contains irregular fibers of hornblende. The pyrrhotite forms reticulating networks among the hornblende fibers, the veinlets of ore lying parallel to the fibers.

3. Stobie Mine, Blezard Township.—The brecciated character is here very pronounced, and the ore contains a large proportion of barren rock-masses of all sizes, as usual filled around with sulphides. Fig. 4 shows the prevailing nature of the more massive ore, with its residual angular and rounded rock-fragments.

Under the microscope, sections of rock, with a small proportion of ore, are made up largely of a fine-grained mixture of plagioclase (labradorite and anorthite) and hypersthene, with small amounts of augite, diallage, and biotite; and magnetite, apatite, and zircon as accessories. Quartz, in varying amount, is also characteristic. The hypersthene is quite abundant, and forms idiomorphic and rounded grains and irregular aggregates; it shows the usual microscopical characters of this mineral. The pyroxenes are, as a rule, quite fresh, but form a mosaic with the feldspar, probably due to crushing. Along certain lines, however, the pyroxenes have altered to a pale-green uralitic hornblende or chlorite.

The relations of the sulphides to the rock-minerals are striking. Following the direction of the altered zones, the sulphides are most prominently developed. A veinlet of chalcopyrite can be traced across one of the sections, following the cleavages, and between the fibers of hornblende and around the fresher grains of the other minerals (Fig. 6). In other cases the partly-altered pyroxene has been more or less replaced by ore, the particles of which are elongated in the direction of the cleavages, and follow these even when they change their direction abruptly. When found in connection with the fresher grains, the

sulphides simply inclose them, following their irregularities and larger cleavages (Fig. 8).

An increasing proportion of ore is accompanied by a corresponding change in the character of the rock. The pyroxenes decrease notably in quantity and finally disappear, giving place to secondary green hornblende, chlorite, and biotite. Both hornblende and biotite are fibrous, and often show deformation, due to strain. The hornblende and other secondary products, in their turn, disappear as the ore increases, and various stages of their replacement can be traced from an almost pure silicate, containing a few specks of ore, to pure sulphide. In intermediate cases the sulphides may preserve very perfectly the fibrous structure of the hornblende or biotite, with little shreds of the mineral marking its original form. In purer ore, still, the dark silicates disappear almost entirely, and the feldspar is filled with inclusions of ore and changed to a confused aggregate of secondary products.

In the latter cases the amount of quartz has increased notably and remains as clear irregular patches through the ore.

4. Frood, or No. 3 Mine, McKim Township.—The ore consists of coarse- and fine-grained pyrrhotite and chalcopyrite. The latter at times occurs in almost pure masses, and is most abundant towards the walls. Barren rock-fragments occur all through the ore-body, presenting the usual breccia, cemented by sulphides.

Microscopic sections show that the rock has undergone considerable alteration. No traces of original pyroxene could be found. The secondary hornblende is bleached and ragged, and is intimately associated with the sulphides, as is the biotite, which is also plentiful. Feldspar in many cases is subordinate, while there is a notable amount of clear quartz, which is apparently secondary. Calcite also appears in small quantities. The sulphides are always found in connection with the dark silicates, and replace them to a greater or less extent.

5. Elsie Mine, Snider Township, and Murray Mine, McKim Township.—The ore-body (Elsie) is situated well within the basic rocks, the granite contact being some distance off. The ore is largely pyrrhotite, with a varying amount of chalcopyrite, which increases towards the foot-wall. The ore is in places largely mixed with rock and may become subordinate

in amount, even in the midst of the deposit. Nearly every piece of ore shows a characteristic breccia of rock in a matrix of sulphides, the rock being either practically barren or having veinlets of mineral irregularly through it (Fig. 9). There are many evidences of movement, as shown by the numerous clay seams impregnated with sulphides and in the schistose and slaty character of the gabbro, which is often polished and slickensided. There are also examples of what appear to be fault-planes and fissures, filled with a mixture of tremolite, quartz, calcite, and ore, the latter very evidently having been introduced subsequent to the movement. The structure at the Murray mine is very similar to that at the Elsie, except that the granite contact is close to the ore-body. The granite pierces the associated "greenstones" (altered sediments?) and is undoubtedly younger.

Microscopic sections of rock with a large amount of ore show that most of the pyroxenes have changed to green fibrous hornblende, though original hypersthene more or less altered is still recognizable. The feldspar is much crushed, and is in an advanced stage of alteration, and often contains hornblende fibers, and parallel veinlets of pyrrhotite along the cleavages (Fig. 12).

The relation of the sulphides to the rock-minerals is of the usual type, *i.e.*, the replacement proceeds along and between the hornblende fibers and lines of weakness and cleavage in other minerals.

6. Mines Around Copper Cliff in Snider and McKim Townships.—This group includes the following mines of the Canadian Copper Co.: Copper Cliff, No. 1, No. 2, No. 4, and No. 5, in different stages of development. Some of the deposits are entirely surrounded by "greenstones," while others have the granite-gneiss as one of the so-called "walls." Dr. Barlow, of the Geological Survey of Canada, is of the opinion that the ore-bearing norite often occurs in more or less completely isolated passages in the "greenstones," and may consist almost entirely of ore.

No. 2 mine (and extension) affords a typical example of the "breccia ore-body." The contact is right at the granite, and the ore-bearing rock has numerous small dikes of the latter through it, and in this case, at least, it seems to be indisputable that the granite is the younger. Near the contact the

granite contains a small amount of ore, and samples at times consist of both acid and basic rock impregnated with sulphides. The brecciated structure is very pronounced, and veinlets of ore occur everywhere through the rock (Fig. 11). There is also evidence of shearing, and secondary quartz-stringers are common.

The Copper Cliff mine belongs to the same brecciated type and has yielded a large number of minerals of secondary origin. (See Part I.)

No. 1 mine in places exhibits a very abrupt transition from rich ore to barren rock. A short distance from the ore-body the rock is slightly mineralized, but on a close examination it is seen that the ore always occurs in small crevices or parting-planes, or other lines of weakness.

Under the microscope, thin sections show that the rock varies from an almost pure hornblende variety, with other minerals in subordinate amount, to more acid varieties, but in all, the dark silicates are in excess. Nearly all the pyroxene has been altered to fibrous green hornblende, though in some sections traces still remain. Quartz is often quite abundant, and the usual accessories are present. The granular nature of the feldspar, and the bent and twisted hornblende and biotite, indicate severe crushing. The sulphides abut sharply against the fresher minerals, but when they are fibrous and broken, they tend to occur between the fibers and grains, more or less complete replacement resulting (Fig. 13).

As the amount of ore increases, the dark silicates disappear largely, leaving areas of clear quartz and feldspar, with the ore sharply defined against their boundaries (Fig. 24). Where the effects of crushing are most pronounced, the sulphides are best developed, and then the replacement extends from these centers along the cleavages and between the hornblende fibers, resulting in a more or less complete substitution of ore.

7. Creighton Mine, Near the Boundary Between Snider and Creighton Townships.—This mine, which has recently been developed by the Canadian Copper Co., is perhaps one of the most remarkable nickel-deposits in the world. The ore-body is very large, and the ore is above the average in richness and purity. Mining is carried on in a huge open-cut, 200 ft. or more across and about 100 ft. deep, in solid ore, with a shaft from the bottom of the pit.

The ore, which is largely pyrrhotite with more or less chalcopyrite, however, contains many masses of barren diorite (norite) all through it, presenting a very characteristic breccia. The rock-fragments vary in size from minute particles to large "boulders," and are both rounded and angular. Where the ore is not too massive to obscure the relations, it presents much the appearance of a conglomerate cemented by sulphides, with numerous ramifying veinlets along the fracture-planes of the rock. Through the ore-body are a number of intrusions of a coarse granitic rock, which often includes fragments of the diorite (norite) breccia. This rock is itself not heavily mineralized, but where it has included fragments of the basic rock these are more or less replaced by ore, and the replacement may extend to the acid rock itself to a lesser extent.

From the evidence collected it would appear that this granitic rock had been intruded into and had included fragments of the diorite at the time of, or after, its brecciation. These fragments have then been partly replaced by ore, the mineralization extending slightly to the acid rock.

There are also two dense fine-grained diabase dikes cutting sharply through the ore-body and having well-defined contacts. These are considered as among the youngest rocks of the district. While they are usually considered to have cut through the ore after its formation, there is a possibility, if the theory of igneous origin is left out of the question, of their being previous to the formation of the deposits.

They do not include fragments of the ore, and their only mineralization is along fissures and joint-planes, the introduction of the sulphides being very evidently later than the intrusion. There has also been a movement in the dikes themselves since their formation, as they are composed of numerous vertical and parallel divisions with smooth polished faces, along which sulphides at times occur. If the dikes were in place previous to the formation of the ore, their compact fine-grained texture would be unfavorable to the action of the ore-bearing solutions, except along parting-planes, while the more coarsely crystalline and crushed diorite would offer an easy passage for the circulating waters.

No conclusive evidence of faulting or shearing could be found in the main pit, but in several of the test-pits sunk in

the vicinity, to determine the extent of the ore-body, abundant proof was available. In these, the rock associated with the ore has been severely crushed and squeezed, so that it presents a schistose and slickensided appearance, and is often much like an amphibolite-schist, with seams of ore on the parting-planes.

If these pits are in a continuation of the main body of ore, as seems probable, we have two different structures resulting from an unequal distribution of the dynamic force which caused them, and probably also due to local differences in the rocks themselves.

In the neighborhood of the Creighton mine, and towards Copper Cliff, the granite frequently cuts the basic rocks and sends dikes through them. What the relation of these rocks is to the ore-bearing variety could not be accurately determined.

Under the microscope, the diorite, or altered norite, presents a somewhat gneissoid appearance, with a large part of the pyroxenes altered to fibrous green hornblende and chlorite. Quartz is present in variable amount.

The sulphides (Fig. 14) are best developed where the effects of crushing are most apparent. Some of the dark silicates have altered to indefinite aggregates of secondary products, which are spotted all through with ore and may even be entirely replaced. The veinlets of sulphides typically follow along the cleavages of hornblende and feldspar, which shows in some cases an advanced stage of alteration. Fig. 18 shows massive ore, with only small residues of unreplaced rock-minerals.

The coarse granitic dikes contain abundant quartz and feldspar, and where they include fragments of the basic rock these show partial replacement, which also extends to the minerals of the acid rock.

8. Gertrude Mine, Creighton Township.—Besides the usual breccia, which is very pronounced, there is abundant evidence of shearing in the different deposits under development (Fig. 20). In No. 1 pit the ore ends very abruptly against a wall of sheared diorite, which is only slightly mineralized along the shear-planes.

Along this contact, and penetrating the rock breccia, a number of small granite dikes have been intruded, which are slightly mineralized. Sheared diorite, together with actinolite

and other secondary minerals, impregnated with ore, is noticeable in all the pits which have been opened up. As these pits are in line, it is probable that the faulting movement embraced them all, but from lack of exposures between, the fault-line could not be traced.

The brecciation and shearing, as well as the intrusion of the granite, evidently took place previous to the introduction of the ore, as all are more or less impregnated with mineral, either as veinlets or between parting-planes.

Under the microscope, the ore-rock is seen to consist very largely of actinolitic and chloritic hornblende, with other minerals of lesser amount.

The relation of the sulphides to the rock-minerals is quite typical (Figs. 16, 17, and 19). Where the hornblende is of the fibrous variety, it is usually associated with ore, and all stages of progressive replacement can be seen. In samples with a large proportion of the ore, the more compact grains of hornblende, as well as the feldspar and quartz, are left as isolated patches in a ground-mass of sulphides, while the fibrous variety has nearly all disappeared.

9. Victoria Mine, Denison Township.—The ore consists of pyrrhotite, with chalcopyrite, which increases in quantity towards the foot-wall in a typical rock-breccia. There is a fault passing through the deposit, and in the secondary minerals formed (actinolite, mica, etc.) the ore occurs in veinlets clearly later than the movement. There is also a considerable development of quartz and calcite intimately mixed through the ore, which cannot be considered as original igneous products.

The microscope shows the ore-rock to be the usual altered norite with the minerals of a diorite. Green fibrous and granular hornblende is predominant. One of the most noticeable features is the large amount of quartz and calcite which remains spotted through the ore when the other minerals have largely disappeared. The replacement of the hornblende and biotite by sulphides is well shown (Fig. 15). The pyrrhotite has many hornblende fibers through it and enters the cleavages of the other minerals in a typical manner.

10. Worthington and Mitchener Mines, Drury Township.—The ore-rock at the Worthington is bounded on the south by a band of dark schistose rock of sedimentary origin, and to the

south of this there is quartzite. The Mitchener mine, about 0.5 mile west of the Worthington, is surrounded by the quartzite. Two varieties of rock are met with in the ore-bodies, namely, coarse- and fine-grained. The coarse-grained variety is sheared and slickensided, and, as a rule, contains little ore, but when it does, it is in the form of veinlets and along the parting-planes. The fine-grained rock has been brecciated, instead of sheared, and numerous rock-fragments of different sizes, surrounded and cemented by sulphides, remain in the ore-bodies (Figs. 22 and 23). Through the ore-body there are also numbers of small lenticular masses of schistose diorite, giving the ore somewhat the appearance of an "augen" gneiss. These are evidently residual portions of the rock which have escaped replacement, and clearly show that the introduction of the ore was subsequent to the movement which caused the shearing and brecciation.

The ore at the Worthington is often very rich, and the nickel-mineral pentlandite occurs quite abundantly.

The fault which occurs at the Victoria seems to be continued through Denison township, embracing the deposits containing niccolite and gersdorffite, through the Worthington, and gradually dying out towards the Mitchener.

Under the microscope, it is seen that the original structure of the rock has been almost entirely obliterated, and green fibrous hornblende and chlorite are the most abundant minerals, and often show the effects of severe crushing. As the quantity of ore increases, the amount of secondary products (epidote, etc.) increases also, and the feldspar is more or less altered and peppered with sulphide grains. Quartz is often present in large amount. Progressive replacement can be traced in both the irregular aggregates and the fibrous masses of hornblende and biotite. In many cases, the introduction of the sulphides appears to start along cleavages, gradually spreading and uniting till only isolated patches of rock-minerals remain, or the whole may be replaced, leaving no trace of the original structure. In this way, reticulating networks of sulphide veinlets form all through the rock, oftentimes ramifying through the areas of quartz and separating the individual grains. Samples of the coarse diorite containing ore present much the same features—*i. e.*, a branching network of sulphide veinlets between the

fibers and along cleavages of hornblende, etc., and separating the different rock-minerals.

11. Levack Township Deposits.—On the northwest are the large deposits in Levack township on the western side of the nickel-belt. These deposits have been thoroughly prospected and opened up to show their extent, and promise to be large contributors of ore in the future.

To the north and west the contact is on the large granite-area, formerly mapped as Laurentian, but which may prove to be much later. At the contact the ore-bearing diorite and granite are mixed up, and the acid rock is impregnated with ore for a short distance, though not to the same extent as the basic rock.

The brecciated nature of the ore-body is very pronounced, and is emphasized on the weathered exposures, where pebbles and boulders of rock stand out from the oxidized sulphides of the gossan.

The vein-like nature of the sulphides is everywhere seen, and is especially well shown in the diamond-drill cores.

As seen under the miscroscope, the rock consists, as usual, largely of secondary fibrous green hornblende, and shows many evidences of severe crushing in the bent and twisted hornblende fibers and the granular aggregates of hornblende and feldspar. The minerals, also, have a marked undulatory extinction. The feldspar is, at times, in idiomorphic individuals, giving the rock a somewhat diabasic aspect.

Good examples of the relation of ore to rock-minerals are presented in some of the sections. One shows a large fragment of fibrous hornblende which has been bent and twisted, with pyrrhotite between the fibers, following all the curves and leaving the comparatively fresh fibers intact. In other places the pyrrhotite has replaced the uralitic hornblende to a greater or less extent, in some cases with such delicacy as to preserve the original fibrous structure perfectly. Where the feldspar and hornblende form granular aggregates, the sulphides form a mass of radiating veinlets around and between the grains, leaving the nucleus unreplaced.

12. North Range. Location, W. D. 16, Wisner Township.—On the northern extension of the nickel-belt a number of promising deposits have been opened up, but so far have not passed the "prospect" stage.

Deposits with good showing have been exploited in lot 6, concession 3, Norman township (Whistle mine); in Bowell township, W. D. 35, 150, 151, and 155, but lack of transportation-facilities has been a serious drawback to more active work. The ore-rock is a fine-grained altered norite, shading to a coarser and more granitic variety to the south, and bounded on the north by the so-called Laurentian granite.

As far as could be determined from the limited exposures, the ore-bodies are very similar to those farther south. That is, they consist of a breccia of almost barren rock cemented by sulphides and with irregular veinlets of ore running through them. Besides the prevailing brecciation, there has been shearing, and numbers of samples of schistose rock are found seamed with ore, especially on the parting-planes.

Microscopically, the rock is seen to be composed largely of secondary hornblende and chlorite, both fibrous and granular. Feldspar is often in idiomorphic crystals, giving the rock a decided ophitic structure. The structure of the sulphides is decidedly vein-like, some of the veinlets continuing across the sections and having numerous accessory ramifications. The ore is most closely associated with the hornblende, and follows between the fibers and grains, conforming to all the irregularities and replacing it partly or wholly, often preserving the fibrous structure very well. As the amount of ore increases, the alteration of the rock-minerals becomes more pronounced, and the sulphides spread all through the section, forming a very characteristic secondary network of reticulating veinlets.

The Wallace Mine, Near the Mouth of the Whitefish River, Lake Huron.—This deposit lies outside what is commonly understood as the "nickel-belt." While essentially the same in some respects, so that it must be considered as genetically similar, it presents certain peculiar features of its own.

The mine is of historic interest, and was opened up as early as 1847 for copper. A year later it was discovered that the ore carried nickel, and a sample containing about two-fifths rock, analyzed by Dr. T. Sterry Hunt, yielded more than 8 per cent. of this metal. After a series of disasters, and the loss of trial-shipments on Lake Huron, the mine was abandoned in 1867, and work has not since been resumed. The deposit occurs at the junction of two small dikes of so-called diorite, in-

truded in the country quartzite. The quartzite at the contact is very black and dense, and has been sheared and slickensided.

Some large masses of heavily-mineralized ore-rock on the dump, which have resisted oxidation, show a decidedly brecciated structure, with sulphides (pyrrhotite, pyrite, and chalcopyrite) cementing the fragments.

The junction of the dikes seems to have been the center of dynamic disturbances, which caused the brecciation and shearing, and formed a favorable place for the circulation and concentration of ore-bearing solutions on a small scale.

There seems little doubt that the ore was precipitated from solution, and the relations are very suggestive when compared with those of the Sudbury deposits.

The microscope shows that the rock has been severely crushed and presents a typical mosaic in places. The hornblende is both granular and fibrous, and gives the rock a schistose appearance. The rock is also much more acidic than the Sudbury types, and contains a good deal of orthoclase and quartz, often in the form of a micropegmatite, differing in this respect also from the others. The ore is mainly in veinlets, surrounding and penetrating the remaining rock-fragments, and replacing the dark silicates (hornblende and biotite) to a greater or less extent. As the amount of ore increases, the dark silicates largely disappear, and the feldspar is broken up into grains, inclosed by ore, and this, together with quartz, is left to a large extent unreplaced, while the remaining fragments of hornblende contain sulphides along the cleavages and between fibers.

The Rossland, B. C., District.—The Josie Mine.[44]—The microstructure of the Rossland ore is so strikingly similar to that from Sudbury that a brief reference will be made to it.

The rock usually associated with the ore is a monzonite, more or less altered. The specimens examined were samples of vein-matter from the Josie (Le Roi No. 2) mine, and presented a decidedly altered and schistose appearance, and contained pyrrhotite and chalcopyrite. Thin sections show that the rock is more or less silicified, and consists largely of secondary fibrous hornblende and biotite, and a smaller amount of feldspar with many fragments of the dark silicate through it.

[44] Material kindly furnished by George H. Dickson, Rossland, B. C.

The relation of the sulphides and rock-minerals is also very similar to that of the Sudbury examples.

They are intimately associated with the dark silicates and form veinlets between the hornblende and biotite fibers, and extend from these in the form of reticulating networks, which in places wholly replace the minerals involved. Where associated with the more granular silicates and quartz, the sulphides form veinlets along the cleavages and around the grains and present the same features as the Sudbury ore, and can only be explained as due to a secondary introduction by means of circulating, ore-bearing solutions.

The Ducktown, Tenn., Deposits.—Figs. 25 and 26[45] show the relations of the ore- and rock-minerals in the Ducktown copper-deposits.

An inspection will show that these are very similar to some of the Sudbury examples. Professor Kemp considers that ore-bearing solutions entered along zones of crushing or faulting, where the material was of a more or less open texture, and replaced silicates and other minerals; the sulphides often insinuating themselves into the broken silicates and abutting sharply against the fresher specimens. In this connection he says: "It therefore seems probable that the replaced material consisted of the crushed and greatly comminuted country-rock, which in this condition would prove an easier prey to the ore-bearing solutions. Where the crushing was most severe, the large ore-bodies are found. Unless some factor of this sort exercised an influence, it seems strange that the process of replacement should cease so sharply against perfectly fresh and unchanged representatives of the presumably replaced minerals."

Summary.

The above results are given in some detail, even at the risk of repetition. But in a problem of this kind it is all-important that the facts should be clearly presented, so as to obtain a grasp of the entire situation and avoid a narrow interpretation based on one or two occurrences, which might not be typical of the whole.

The investigations covering the whole field of the nickel-

[45] From Professor Kemp's paper, The Deposits of Copper-Ores at Ducktown, Tenn., *Trans.*, xxxi., 255, 256 (1901).

range show that all the deposits have certain prominent features in common.

1. Brecciation, with accompanying faulting, and shearing are everywhere characteristic. This is shown not only on a large scale, but is also corroborated by the microscopical relations.

2. The main brecciation and shearing took place previous to the formation of the ore-bodies proper.

3. The abrupt change from massive sulphides to barren rock, so often noticed, seems irreconcilable with the theory of magmatic segregation, and it is also difficult to imagine how the included rock-fragments could retain their angular form if they were once part of, or floated in, a molten magma.

4. The ore prevailingly occurs as a cement for the brecciated rock-fragments and along shear-planes.

5. The rocks associated with the ore are all members of the gabbro family and can generally be referred to norite.

6. The rocks are more or less altered and now resemble diorite, the original pyroxene having in nearly all cases changed to a fibrous green hornblende and chlorite. Where original pyroxene remains (*e. g.*, at the Stobie and Mount Nickel mines), the structure is markedly brecciated.

7. The effects of metamorphism and the development of secondary hornblende are most marked near the ore-bodies, and diminish away from them.[46]

8. In general, the more complete the alteration of the rock, the more complete has been its replacement by sulphides.

9. The relation of the ore to the rock-minerals is practically identical throughout the whole district. In all cases the tendency of the sulphides is to occur along planes of weakness and in connection with the fibrous minerals.

Occasionally the relations of the pyrrhotite to the silicates suggest that it is an original constituent of the rock and one of the first minerals to crystallize from the magma. This is seen at times in the less altered specimens some distance from the ore-bodies.

The amount of this apparently original pyrrhotite is, however, always very subordinate, and is probably no more than might reasonably be expected in a gabbro.

[46] Compare Walker, *Quarterly Journal of the Geological Society*, vol. liii., No. 209, p. 47 *et seq.* (Feb., 1897).

So that while a small percentage of the pyrrhotite may be original, the main contention still holds, namely, that the sulphides are essentially and predominantly secondary.

10. Secondary quartz and calcite are often present in the ore in appreciable amount, while they are insignificant or lacking at a little distance.[47]

11. Sulphides are practically lacking in the rock a short distance from the ore. The rock-fragments included in the deposit are also comparatively free from ore, except in veinlets.

12. The relation of the magnetite to the rock-minerals is in marked contrast to that of the sulphides, the former being always in more or less rounded grains in the dark silicates and generally primary.

13. With regard to the relations of the sulphides to the rock-minerals themselves, several different types might be differentiated. These types are, however, all alike in kind, and several may occur in a single specimen.

(*a*) Replacement starting between and extending along the fibers of hornblende, often resulting in a pseudomorph of ore after this mineral.

(*b*) Replacement along cleavages of the more compact and less altered minerals, breaking them up into grains and, at times, forming complete pseudomorphs.

(*c*) Replacement between crystals and fragments of the same or different minerals, often extending into the mineral substance, when it could be classed under (*a*) or (*b*).

(*d*) Replacement along planes or zones of parting and shearing, the veinlets being in general parallel and ramifying through the neighboring minerals as indicated in (*a*), (*b*) and (*c*).

(*e*) In the more crushed and granular examples, where the rock-minerals are much altered, the sulphides are peppered all through them and form an intricate and ramifying network of veinlets in the rock, at times completely replacing the minerals around certain centers.

(*f*) The dark silicates fall the easiest prey to the ore-bearing solutions, but many instances are noted in which the feldspar suffers. This is generally the case where the crushing and shearing have been most severe and the mineral is partly or wholly changed to secondary products. As a rule, though not

[47] Walker, *loc. cit.*

invariably, this change is especially noticeable where the mineralization of the rock is most pronounced.

14. A comparison of the Sudbury deposits with those of Rossland, B. C., and Ducktown, Tenn., shows many remarkable and essential points of similarity. These deposits are now proved beyond all reasonable doubt to be of secondary aqueous origin, and this, aside from direct evidence, points strongly to a similar origin for the Sudbury occurrences.

Relation of Chalcopyrite to Pyrrhotite.—From the massive nature of the sulphides, very little can be accurately determined as to the paragenesis of the minerals. There are, however, certain relations existing between the chalcopyrite and the pyrrhotite which may help to explain it.

1. In a number of cases where copper is predominant, the ore consists of numerous small parallel veinlets of pyrrhotite and chalcopyrite very intimately associated. This is well illustrated by examples from the Copper Cliff and Creighton mines (Figs. 10 and 21). The same relation is a prominent feature of the Rossland ore, and hand-specimens from the two localities are almost indistinguishable.

2. The chalcopyrite is usually most strongly concentrated near the outside of the deposits, especially towards the so-called foot-wall. As a rule, the proportion of chalcopyrite in the main ore-body is rather small, and it tends to form fairly-pure masses without much pyrrhotite. Taking these facts into consideration, it seems likely that the pyrrhotite at first constituted the largest part of the ore-body. Later, due to some dynamic movement, opening up passages through the ore-bodies, especially towards the outer limits, copper-bearing solutions entered and deposited their mineral contents among the rock-masses and partly replaced pyrrhotite along certain lines. In some deposits, as at the Copper Cliff, where copper-minerals predominate, the fracturing may have been greater and the solutions more active or concentrated.

It is also possible that the copper disseminated in the upper part of the ore-bodies, now eroded, has been secondarily deposited by downward-moving currents, but this does not seem to have been the case to any great extent. In the first place, there is very little in the way of an oxidized gossan, and the ground-water level is comparatively near the surface. Secondly,

there is little, if any, indication of this secondary change in the way of enriched sulphides which accompany the process.

Pyrrhotite is quite generally admitted to be a product of primary concentration by upward-moving solutions in a strongly reducing atmosphere, and if any considerable concentration by downward-moving waters had taken place, we would expect to find the pyrrhotite largely oxidized or removed entirely. It is, however, a notable fact that when the thin surface-covering is removed, the pyrrhotite appears perfectly fresh and with no appreciable admixture of secondary minerals, such as are formed in the process of secondary enrichment.

Source of the Metals.—What the exact sequence of events leading up to the formation of the ore-bodies and the immediate source of the metallic contents was, is not yet satisfactorily settled. The question involves many intricate problems, both of a local and a general nature, and with the evidence at hand an authoritative discussion would be premature.

The metamorphic processes appear to have been very complicated, and are still more obscured by the later alteration due to the mineralizing solutions.

Pyrrhotite is a product of many metamorphic processes and may be formed in any of the classes designated by Lindgren—dynamo, hydro-thermal, solfataric, or contact.[48]

Under which head the metamorphism of the Sudbury district could be accurately classified, it is difficult to say. Indeed, it might be considered as a combination dynamo, hydro-thermal, and solfataric. From a study of the history of the district, however, it is quite evident that it was a region of vulcanism and metamorphic processes on a large scale, and the immense stores of heat and energy involved could be readily available as stimulators of the circulation and chemical activity of the mineral solutions, so that the theory of an aqueous origin presents nothing at all unreasonable.

Hydrogen sulphide is so common a constituent of mineral and thermal springs that its presence in the mineral solutions can be assumed. From the nature of the deposits, the ore-bearing solutions were probably highly charged with alka-

[48] W. Lindgren, Nevada City and Grass Valley Districts, *Seventeenth Annual Report, U. S. Geological Survey*, Pt. II., p. 90 (1895-96).

line carbonates and hydrogen sulphide, but with subordinate amounts of carbon dioxide.

The microscopical investigations show that the dark silicates are often bleached and robbed of iron, or else "resorbed," forming aggregates of magnetite grains. It is thus possible that a certain amount of the iron was derived from the alteration of the minerals of the replaced zone as well as from extraneous sources. The source of the nickel may, to some extent, have been the associated rocks, which contain small amounts, but it seems more probable that the larger part was derived from greater depths traversed by the circulating waters.

Many of those who are familiar with the district, and who have discarded the theory of a direct "magmatic segregation," still consider that there was a preliminary concentration of metals with the intrusion of the norite, and that the ore-bodies assumed their present position and dimensions by subsequent processes.

This may, to a certain extent, be true, and the presence of small quantities of what appears to be original pyrrhotite in the ore-rock is cited in support of this view. Moreover, this theory does not involve many of the difficulties of the first. Still, a consideration of the whole subject and the relations involved seems to indicate that this "preliminary concentration" was comparatively slight, and appeal must be made to a more distant source of the metals, probably minutely disseminated in the rocks through which the depositing solutions passed.

In conclusion, it might be safely stated that at present the whole weight of the evidence points to the secondary formation of the Sudbury ore-bodies as replacements along crushed and faulted zones, with only minor indications of open cavities.

Previous observers have naturally been impressed by the massive character of the sulphides, in which are found the minerals of the inclosing rock, and this seems to fall in readily with the idea of an igneous origin.

The clue to the interpretation of the matter, however, appears to be furnished by the leaner material, where the relations have not been obscured or obliterated by the excessive development of the sulphides.

The universal association of these ores with essentially similar rocks is also striking. That the norite (or gabbro) has an

intimate connection with the development of the ores cannot be doubted, but in just what way they are related is not clear.

After a review of the ideas held of these and similar deposits elsewhere, it will be seen that the evidence adduced in support of the igneous hypothesis can be equally well, if not better, interpreted on the basis of replacement, while many of the observed phenomena cannot be satisfactorily explained on the assumptions of the old hypothesis.

With the additional light thrown on the subject by these investigations, there seems to be no reasonable doubt left as to the true nature of the deposits, and it may be confidently expected that future work will give additional weight to the views here advanced.

Finally, with regard to my personal connection with the matter, it may be well to say that, in taking up the work, I went into the field with an open mind and for the sole purpose of interpreting the phenomena as they were presented by the facts, without being hampered by any preconceived theories. I had always been taught to regard the deposits as essentially of igneous origin, and this theory was, of course, uppermost in my mind. But as instance after instance of the relations in the field was presented in the different deposits, the "igneous" theory was not sufficient to explain the facts. Then, on calmly studying the material collected in the laboratory, the conviction became a certainty, and I present my views only for the purpose of throwing as much light as possible on these complicated problems.

Aside from the main contention that the deposits are replacements, any arguments advanced as to the actual source, manner of concentration, and paragenesis of the ore may be regarded as largely tentative and as inviting discussion, by which we may hope to arrive at more definite conclusions as to the actual processes and sequence of events, culminating in these remarkable bodies of ore as we find them to-day.

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No. 19.

The Genesis of the Copper-Deposits of Clifton-Morenci, Arizona.*

BY WALDEMAR LINDGREN, WASHINGTON, D. C.

(Lake Superior Meeting, September, 1904. *Trans.*, xxxv., 511.)

CONTENTS.

	PAGE
Topography and Geology,	518
Occurrence and General Features of Ore-Deposits,	520
Metamorphic Processes,	522
Contact-Metamorphism,	522
Hydrothermal Metamorphism,	529
Relation of Contact- and Hydrothermal Metamorphism,	530
Processes Due to Oxidation and Hydration in the Oxidized Zone,	531
Sulphate Waters,	532
Processes in Fissure-Veins,	532
Oxidation of Chalcocite,	534
Oxidizing-Processes in Limestone,	535
Oxidizing-Processes in Shale,	536
Paragenesis,	536
Characteristics of Deposits,	537
Deposits of Carbonates and Oxides in Limestone and Shale,	537
Fissure-Veins and Related Deposits of Morenci Type,	539
The Coronado Type of Veins,	543
Gold-Bearing Veins,	544
Conditions of Ground-Water,	544
Depth of Oxidized Zone,	545
Fluid-Inclusions,	545
In Granite,	546
In Metamorphic Limestones,	546
In Porphyry,	546
In Vein-Quartz,	549
Summary of Genesis,	551
Genetic Classification,	556

THE following pages are a résumé of some of the conclusions reached during a study of the copper-deposits near Clifton. The field-work was finished in 1902 and a complete report is now in the press. A preliminary description of the district was published in 1903, in *Bulletin U. S. Geological Survey, No.* 213, pp. 133–140.

* Published by the permission of the Director of the U. S. Geological Survey.

The Clifton mines, always important, are at present the largest in the territory, the output in 1902 having reached 50,000,000 lb. of copper, chiefly divided between the two principal producers, the Arizona and the Detroit copper companies. The Shannon Copper Co. also contributed to this figure, and its output has greatly increased since then. The total output of the district to the end of the year 1903 is estimated at a value of about $49,000,000.

Topography and Geology.

Clifton is situated on the San Francisco river, a few miles above its confluence with the Gila river, in the southeastern part of the territory, and not many miles from the New Mexican boundary. An irregular mountain region, without well-defined ranges, lies here north of the broad, detritus-filled valley of the Gila river, which has an elevation of about 3,000 feet. The highest elevations in the mountains scarcely attain 8,000 feet.

Between the San Francisco river and Eagle creek, both tributaries to the Gila river from the north, a core of older rocks of about 70 sq. miles is exposed, consisting of pre-Cambrian granites, Cambrian quartzites, Paleozoic limestones, and a capping-formation of Cretaceous beds—all intruded by post-Cretaceous granitic porphyries. This older core, which seems to represent the broken-down edge of the great plateau-province, is completely surrounded and largely covered by volcanic flows of Tertiary age, including basalts, andesites and rhyolites, which have been extensively eroded; hence the lack of regularity so plainly apparent in the mountain complex.

The copper-deposits are all contained in the older rocks and distinctly antedate the Tertiary lavas.

The sedimentary rocks rest on a basement of red, coarse granite, forming two great buttresses, the Coronado and the Copper King mountains, both rising more than 3,000 ft. above the San Francisco river.

The Paleozoic series consists of the following-named formations:

Modoc limestone. (Lower Carboniferous.)	Up to 200 ft. thick, heavy-bedded, gray limestones of great purity, with some equally pure dolomites at the base.
Morenci shale. (Devonian?)	100 ft. of clay-shales, sometimes underlain by 75 ft. of argillaceous limestone.
Longfellow limestone. (Ordovician.)	Up to 400 ft. of limestones, partly cherty and, near the base, containing sandy beds. Some of these strata are dolomitic.
Coronado quartzite. (Cambrian?)	200 ft. of reddish, quartzitic sandstones resting on granite. Lowest member is a quartzitic conglomerate.

The three upper divisions contain characteristic fossils, while only a few small *Lingula* shells have been found in the Coronado quartzite.

The Cretaceous series rests unconformably on the Modoc limestone and consists of a succession of clay-shales and dark sandstones at least 200 ft. thick. Scant fossils indicate that it belongs to the Fort Benton horizon.

Gentle dips, rarely above 20° and generally directed westward, characterize the sedimentary rocks.

All of the above-mentioned rocks are intruded by a great stock of porphyry which extends in a northeasterly direction between the foothills near Eagle creek across to the great Copper King granite ridge overlooking San Francisco river. The main stock, which is about 8 miles long and up to a mile and a half wide, breaks up, at the southwest end, into a network of irregular dikes and sheets, and, at the northeast, into a system of northeasterly-trending dikes cutting through the granite. Laccolithic masses of porphyry occur in the Cretaceous shales and sandstones. The rock of the main stock ranges from a granite-porphyry to a quartz-monzonite porphyry. The sills and laccoliths are usually composed of diorite-porphyry, but the different types of rock are clearly facies of the same magma, connected by transitions and forming a single geological unit. Dikes of diabase occur in a few places.

The intrusion of the poryhyry took place during the latest Cretaceous or the earlier Tertiary, and was accompanied by great disturbances in the immediately adjoining rocks, particularly well noticeable in the Paleozoic sediments; but these disturbances of the strata did not extend far from the contacts.

The intrusion of the porphyry was followed by important

structural movements. The surface of the granite, together with the whole covering sedimentary series, was buckled into dome-shaped folds and then extensively fractured, the blocks sinking successively deeper towards the valley and settling unequally around the two great buttresses, or "horsts," the Coronado and Copper King mountains, the maximum throw of the normal faults being 3,000 feet.

An epoch of erosion followed, but floods of Tertiary lavas soon surrounded and largely covered the old rocks which have only lately emerged by the energetic action of a second epoch of erosion. The effects of the large faulting-movements, which preceded the lavas, are still visible in the greater topographic features of the region, especially in the bold escarpment of the Copper King ridge.

Occurrence and General Features of the Ore-Deposits.

The geographical distribution of the copper-deposits is practically coextensive with the great porphyry stock and its dike-systems. The deposits occur either in the porphyry or close to its contacts, or along dikes of porphyry in some other rock. Areas in which no intrusions have taken place are practically barren. This intimate connection with the porphyry is certainly a most important fact. There is only one small division of deposits which deviates from this rule—namely, that connected with the diabase-dikes.

Practically all types of deposits contain copper as the most valuable metal. Gold and silver occur, as a rule, only in minute quantities, except in some of the outlying districts where they become of more importance. The two most important mining-centers, Morenci and Metcalf, which are 3 miles apart, are both situated at the main contact of the porphyry stock and the series of Paleozoic limestones. Elsewhere the intrusive rock generally adjoins granite or Cretaceous sediments.

The ores consist of chalcocite, chalcopyrite, malachite, azurite, chrysocolla, brochantite, cuprite, and native copper. Covellite and bornite are practically absent. Brochantite, a basic copper sulphate, is very commonly present, especially in the oxidized veins in porphyry; and, in fact, constitutes in places an important ore. On account of its similarity to, and intimate intergrowth with, malachite it has usually been overlooked.

The following-named minerals have been found:—Native copper, native gold, quartz, chalcedony, rutile, magnetite, hematite, limonite, pyrolusite, coronadite (a new mineral, chiefly PbO and MnO_2), cuprite, pyrite, chalcopyrite, zinc-blende, galena, molybdenite, chalcocite, diopside, tremolite, garnet, epidote, muscovite, chlorite, serpentine, asbestos, kaolin, willemite, calamine, dioptase, chrysocolla, copper pitch ore, morencite (a new mineral, chiefly a ferric silicate), calcite, dolomite, zinc carbonate, malachite, azurite, libethenite (copper phosphate, not previously found in the United States), brochantite, alunite, gypsum, spangolite (basic chloro-sulphate of copper and aluminum), chalchanthite, goslarite, epsomite and gerhardtite (a basic copper nitrate forming green crusts on weathered surfaces of porphyry, and associated in these with a copper chloride, possibly atacamite).

The deposits with payable copper-ore take many widely differing forms, as follows:—

Deposits in limestone and shale, not connected with fissure-veins.
- Irregular bodies near contacts of main stock or dikes.
- Tabular bodies near contacts of main stock or dikes following stratification.
- Tabular bodies, following contacts of porphyry dike (all of these carry oxidized ores, almost exclusively; rarely chalcocite).

Fissure-veins.
- Normal veins in porphyry or in any of the other rocks near porphyry-contacts. Include central veins and surrounding partly-replaced porphyry forming together a lode. Carry chalcocite as the important ore; in upper levels also sometimes oxidized ores.
- Normal veins, following porphyry dikes in granite. Chalcocite and oxidized copper-ores.
- Normal veins following diabase-dikes. Chalcocite and oxidized copper-ores.

Stock-werks. Irregular disseminations in porphyry, quartzite and other rocks. Contain chalcocite and oxidized copper-ores.

The above classification is based on occurrence and form, and a more general genetic system, given below, shows a somewhat different arrangement.

Native copper, all of the oxy-salts of copper, and chalcocite are wholly secondary minerals produced by direct or indirect oxidation from primary pyritic ores. In all of the divisions given above, this primary ore consists of pyrite and chalcopyrite, with some zinc-blende and molybdenite. The scant gangue of the veins consists of quartz, while the deposits in

the first division are usually accompanied by garnet, epidote, magnetite, diopside, tremolite, or their products of oxidation.

Metamorphic Processes.

The region described in this paper is practically unaffected by regional or dynamic metamorphism, and even the ordinary hydro-metamorphism has altered the rocks but little, producing some slight changes in granite and porphyry and introducing cherts into the limestones. Epidote, chlorite, and a little pyrite are apt to develop in the hornblendic phases of the porphyry.

Contact-Metamorphism.

Contacts of porphyry with sedimentary rocks often show typical instances of this metamorphism. The granite-porphyry and the quartz-monzonite porphyry show themselves most effective in this direction, while there is usually but little metamorphic action at the contacts of the diorite-porphyry. The effect seems in direct proportion to the amount of quartz contained in the porphyry. Granite and quartzite are unaltered; the shales and sandstones of the Cretaceous series are hardened and baked. The shales change, as a rule, only at the immediate contact, to dense, greenish hornfels.

The Paleozoic limestone-series comes in contact with the main stock in two places—at Morenci and at Metcalf. In both places extensive copper-deposits are encountered. Dikes also occur at both places and along some of these radiating out into the unaltered areas the metamorphic processes may be examined to best advantage.

In studying the phenomena along dikes, it is found that the metamorphism varies greatly in the different strata, and even in apparently similar limestone layers there may be great difference in the degree of alteration. A well-defined dike 50 ft. wide on Modoc mountain was studied with special care as it cut through all of the formations present. Where contained in the Longfellow limestone the metamorphism extends at most 20 ft. outward into the limestone, and generally only a few feet. Garnet, epidote, diopside, specularite, and magnetite are the minerals which form abundantly by metasomatic replacement along the contacts, and intergrown with them are chalcopyrite, pyrite, and zinc-blende, unquestionably of contemporaneous

formation. The contact metamorphic limestone has certainly a very different composition from the unaltered rock, and it is apparent that much silica, iron, copper and zinc, at least, have been added. Epidote often forms in considerable quantities close to the contacts, while a little farther away garnet prevails. The Morenci shales overlying the Longfellow limestone are hardened and baked, but not materially altered in composition. Finally, when the dike enters the pure limestone of the Modoc formation, garnet forms in enormous quantities from the latter; the metamorphism exerted by the dike here merges into that affecting the whole block of limestone, due to the contact of the main stock of porphyry.

The principal metamorphic area at Morenci is about 2 miles long; its width is from 1,000 to 1,500 feet. The Modoc formation, however, has been affected to an extraordinary degree, and extends as a stratum of garnet and magnetite 2,000 ft. distant from the contact between almost unaltered Devonian and Cretaceous sediments.

The Longfellow limestone, though somewhat irregularly altered, is, next to the contact, generally transformed into a coarsely granular rock of garnet, epidote, diopside, magnetite, pyrite, zinc-blende, and chalcopyrite, and there is a most decided change of composition, chiefly consisting in additions of silica and iron. Other parts are less altered, but contain much magnetite, together with the sulphides mentioned, disseminated through a medium-grained crystalline mass of the carbonates of lime and magnesia. The development of magnetite, metasomatically, is a most pronounced feature of the process. Looking at the formation as a whole; sulphur, iron, copper and zinc have certainly been added, and probably also silica and magnesia. Large masses of magnetite, locally used as a flux, have been mined at this horizon.

The Morenci shales have suffered a change to dense, greenish hornfels with a development of amphibole and, in places, also muscovite. Pyrite and magnetite are also present, but on the whole, the change in composition is probably slight.

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there is little, if any, indication of this secondary change in the way of enriched sulphides which accompany the process.

Pyrrhotite is quite generally admitted to be a product of primary concentration by upward-moving solutions in a strongly reducing atmosphere, and if any considerable concentration by downward-moving waters had taken place, we would expect to find the pyrrhotite largely oxidized or removed entirely. It is, however, a notable fact that when the thin surface-covering is removed, the pyrrhotite appears perfectly fresh and with no appreciable admixture of secondary minerals, such as are formed in the process of secondary enrichment.

Source of the Metals.—What the exact sequence of events leading up to the formation of the ore-bodies and the immediate source of the metallic contents was, is not yet satisfactorily settled. The question involves many intricate problems, both of a local and a general nature, and with the evidence at hand an authoritative discussion would be premature.

The metamorphic processes appear to have been very complicated, and are still more obscured by the later alteration due to the mineralizing solutions.

Pyrrhotite is a product of many metamorphic processes and may be formed in any of the classes designated by Lindgren—dynamo, hydro-thermal, solfataric, or contact.[48]

Under which head the metamorphism of the Sudbury district could be accurately classified, it is difficult to say. Indeed, it might be considered as a combination dynamo, hydro-thermal, and solfataric. From a study of the history of the district, however, it is quite evident that it was a region of vulcanism and metamorphic processes on a large scale, and the immense stores of heat and energy involved could be readily available as stimulators of the circulation and chemical activity of the mineral solutions, so that the theory of an aqueous origin presents nothing at all unreasonable.

Hydrogen sulphide is so common a constituent of mineral and thermal springs that its presence in the mineral solutions can be assumed. From the nature of the deposits, the ore-bearing solutions were probably highly charged with alka-

[48] W. Lindgren, Nevada City and Grass Valley Districts, *Seventeenth Annual Report, U. S. Geological Survey*, Pt. II., p. 90 (1895-96).

line carbonates and hydrogen sulphide, but with subordinate amounts of carbon dioxide.

The microscopical investigations show that the dark silicates are often bleached and robbed of iron, or else "resorbed," forming aggregates of magnetite grains. It is thus possible that a certain amount of the iron was derived from the alteration of the minerals of the replaced zone as well as from extraneous sources. The source of the nickel may, to some extent, have been the associated rocks, which contain small amounts, but it seems more probable that the larger part was derived from greater depths traversed by the circulating waters.

Many of those who are familiar with the district, and who have discarded the theory of a direct "magmatic segregation," still consider that there was a preliminary concentration of metals with the intrusion of the norite, and that the ore-bodies assumed their present position and dimensions by subsequent processes.

This may, to a certain extent, be true, and the presence of small quantities of what appears to be original pyrrhotite in the ore-rock is cited in support of this view. Moreover, this theory does not involve many of the difficulties of the first. Still, a consideration of the whole subject and the relations involved seems to indicate that this "preliminary concentration" was comparatively slight, and appeal must be made to a more distant source of the metals, probably minutely disseminated in the rocks through which the depositing solutions passed.

In conclusion, it might be safely stated that at present the whole weight of the evidence points to the secondary formation of the Sudbury ore-bodies as replacements along crushed and faulted zones, with only minor indications of open cavities.

Previous observers have naturally been impressed by the massive character of the sulphides, in which are found the minerals of the inclosing rock, and this seems to fall in readily with the idea of an igneous origin.

The clue to the interpretation of the matter, however, appears to be furnished by the leaner material, where the relations have not been obscured or obliterated by the excessive development of the sulphides.

The universal association of these ores with essentially similar rocks is also striking. That the norite (or gabbro) has an

intimate connection with the development of the ores cannot be doubted, but in just what way they are related is not clear.

After a review of the ideas held of these and similar deposits elsewhere, it will be seen that the evidence adduced in support of the igneous hypothesis can be equally well, if not better, interpreted on the basis of replacement, while many of the observed phenomena cannot be satisfactorily explained on the assumptions of the old hypothesis.

With the additional light thrown on the subject by these investigations, there seems to be no reasonable doubt left as to the true nature of the deposits, and it may be confidently expected that future work will give additional weight to the views here advanced.

Finally, with regard to my personal connection with the matter, it may be well to say that, in taking up the work, I went into the field with an open mind and for the sole purpose of interpreting the phenomena as they were presented by the facts, without being hampered by any preconceived theories. I had always been taught to regard the deposits as essentially of igneous origin, and this theory was, of course, uppermost in my mind. But as instance after instance of the relations in the field was presented in the different deposits, the "igneous" theory was not sufficient to explain the facts. Then, on calmly studying the material collected in the laboratory, the conviction became a certainty, and I present my views only for the purpose of throwing as much light as possible on these complicated problems.

Aside from the main contention that the deposits are replacements, any arguments advanced as to the actual source, manner of concentration, and paragenesis of the ore may be regarded as largely tentative and as inviting discussion, by which we may hope to arrive at more definite conclusions as to the actual processes and sequence of events, culminating in these remarkable bodies of ore as we find them to-day.

Acknowledgments.—The writer wishes especially to acknowledge his indebtedness to Professor Kemp, of Columbia University; Dr. Goodwin, Director of the School of Mining, Kingston, Ontario; Prof. W. G. Miller, Provincial Geologist of Ontario; and J. Walter Wells, late Chemist to the Ontario Bureau of Mines, for assistance and kindly interest in the work.

No. 19.

The Genesis of the Copper-Deposits of Clifton-Morenci, Arizona.*

BY WALDEMAR LINDGREN, WASHINGTON, D. C.

(Lake Superior Meeting, September, 1904. *Trans.*, XXXV., 511.)

CONTENTS.

	PAGE
Topography and Geology,	518
Occurrence and General Features of Ore-Deposits,	520
Metamorphic Processes,	522
Contact-Metamorphism,	522
Hydrothermal Metamorphism,	529
Relation of Contact- and Hydrothermal Metamorphism,	530
Processes Due to Oxidation and Hydration in the Oxidized Zone,	531
Sulphate Waters,	532
Processes in Fissure-Veins,	532
Oxidation of Chalcocite,	534
Oxidizing-Processes in Limestone,	535
Oxidizing-Processes in Shale,	536
Paragenesis,	536
Characteristics of Deposits,	537
Deposits of Carbonates and Oxides in Limestone and Shale,	537
Fissure-Veins and Related Deposits of Morenci Type,	539
The Coronado Type of Veins,	543
Gold-Bearing Veins,	544
Conditions of Ground-Water,	544
Depth of Oxidized Zone,	545
Fluid-Inclusions,	545
In Granite,	546
In Metamorphic Limestones,	546
In Porphyry,	546
In Vein-Quartz,	549
Summary of Genesis,	551
Genetic Classification,	556

THE following pages are a résumé of some of the conclusions reached during a study of the copper-deposits near Clifton. The field-work was finished in 1902 and a complete report is now in the press. A preliminary description of the district was published in 1903, in *Bulletin U. S. Geological Survey, No.* 213, pp. 133–140.

* Published by the permission of the Director of the U. S. Geological Survey.

The Clifton mines, always important, are at present the largest in the territory, the output in 1902 having reached 50,000,000 lb. of copper, chiefly divided between the two principal producers, the Arizona and the Detroit copper companies. The Shannon Copper Co. also contributed to this figure, and its output has greatly increased since then. The total output of the district to the end of the year 1903 is estimated at a value of about $49,000,000.

Topography and Geology.

Clifton is situated on the San Francisco river, a few miles above its confluence with the Gila river, in the southeastern part of the territory, and not many miles from the New Mexican boundary. An irregular mountain region, without well-defined ranges, lies here north of the broad, detritus-filled valley of the Gila river, which has an elevation of about 3,000 feet. The highest elevations in the mountains scarcely attain 8,000 feet.

Between the San Francisco river and Eagle creek, both tributaries to the Gila river from the north, a core of older rocks of about 70 sq. miles is exposed, consisting of pre-Cambrian granites, Cambrian quartzites, Paleozoic limestones, and a capping-formation of Cretaceous beds—all intruded by post-Cretaceous granitic porphyries. This older core, which seems to represent the broken-down edge of the great plateau-province, is completely surrounded and largely covered by volcanic flows of Tertiary age, including basalts, andesites and rhyolites, which have been extensively eroded; hence the lack of regularity so plainly apparent in the mountain complex.

The copper-deposits are all contained in the older rocks and distinctly antedate the Tertiary lavas.

The sedimentary rocks rest on a basement of red, coarse granite, forming two great buttresses, the Coronado and the Copper King mountains, both rising more than 3,000 ft. above the San Francisco river.

The Paleozoic series consists of the following-named formations:

Modoc limestone. (Lower Carboniferous.)	Up to 200 ft. thick, heavy-bedded, gray limestones of great purity, with some equally pure dolomites at the base.
Morenci shale. (Devonian?)	100 ft. of clay-shales, sometimes underlain by 75 ft. of argillaceous limestone.
Longfellow limestone. (Ordovician.)	Up to 400 ft. of limestones, partly cherty and, near the base, containing sandy beds. Some of these strata are dolomitic.
Coronado quartzite. (Cambrian?)	200 ft. of reddish, quartzitic sandstones resting on granite. Lowest member is a quartzitic conglomerate.

The three upper divisions contain characteristic fossils, while only a few small *Lingula* shells have been found in the Coronado quartzite.

The Cretaceous series rests unconformably on the Modoc limestone and consists of a succession of clay-shales and dark sandstones at least 200 ft. thick. Scant fossils indicate that it belongs to the Fort Benton horizon.

Gentle dips, rarely above 20° and generally directed westward, characterize the sedimentary rocks.

All of the above-mentioned rocks are intruded by a great stock of porphyry which extends in a northeasterly direction between the foothills near Eagle creek across to the great Copper King granite ridge overlooking San Francisco river. The main stock, which is about 8 miles long and up to a mile and a half wide, breaks up, at the southwest end, into a network of irregular dikes and sheets, and, at the northeast, into a system of northeasterly-trending dikes cutting through the granite. Laccolithic masses of porphyry occur in the Cretaceous shales and sandstones. The rock of the main stock ranges from a granite-porphyry to a quartz-monzonite porphyry. The sills and laccoliths are usually composed of diorite-porphyry, but the different types of rock are clearly facies of the same magma, connected by transitions and forming a single geological unit. Dikes of diabase occur in a few places.

The intrusion of the poryhyry took place during the latest Cretaceous or the earlier Tertiary, and was accompanied by great disturbances in the immediately adjoining rocks, particularly well noticeable in the Paleozoic sediments; but these disturbances of the strata did not extend far from the contacts.

The intrusion of the porphyry was followed by important

structural movements. The surface of the granite, together with the whole covering sedimentary series, was buckled into dome-shaped folds and then extensively fractured, the blocks sinking successively deeper towards the valley and settling unequally around the two great buttresses, or "horsts," the Coronado and Copper King mountains, the maximum throw of the normal faults being 3,000 feet.

An epoch of erosion followed, but floods of Tertiary lavas soon surrounded and largely covered the old rocks which have only lately emerged by the energetic action of a second epoch of erosion. The effects of the large faulting-movements, which preceded the lavas, are still visible in the greater topographic features of the region, especially in the bold escarpment of the Copper King ridge.

Occurrence and General Features of the Ore-Deposits.

The geographical distribution of the copper-deposits is practically coextensive with the great porphyry stock and its dike-systems. The deposits occur either in the porphyry or close to its contacts, or along dikes of porphyry in some other rock. Areas in which no intrusions have taken place are practically barren. This intimate connection with the porphyry is certainly a most important fact. There is only one small division of deposits which deviates from this rule—namely, that connected with the diabase-dikes.

Practically all types of deposits contain copper as the most valuable metal. Gold and silver occur, as a rule, only in minute quantities, except in some of the outlying districts where they become of more importance. The two most important mining-centers, Morenci and Metcalf, which are 3 miles apart, are both situated at the main contact of the porphyry stock and the series of Paleozoic limestones. Elsewhere the intrusive rock generally adjoins granite or Cretaceous sediments.

The ores consist of chalcocite, chalcopyrite, malachite, azurite, chrysocolla, brochantite, cuprite, and native copper. Covellite and bornite are practically absent. Brochantite, a basic copper sulphate, is very commonly present, especially in the oxidized veins in porphyry; and, in fact, constitutes in places an important ore. On account of its similarity to, and intimate intergrowth with, malachite it has usually been overlooked.

The following-named minerals have been found:—Native copper, native gold, quartz, chalcedony, rutile, magnetite, hematite, limonite, pyrolusite, coronadite (a new mineral, chiefly PbO and MnO_2), cuprite, pyrite, chalcopyrite, zinc-blende, galena, molybdenite, chalcocite, diopside, tremolite, garnet, epidote, muscovite, chlorite, serpentine, asbestos, kaolin, willemite, calamine, dioptase, chrysocolla, copper pitch ore, morencite (a new mineral, chiefly a ferric silicate), calcite, dolomite, zinc carbonate, malachite, azurite, libethenite (copper phosphate, not previously found in the United States), brochantite, alunite, gypsum, spangolite (basic chloro-sulphate of copper and aluminum), chalchanthite, goslarite, epsomite and gerhardtite (a basic copper nitrate forming green crusts on weathered surfaces of porphyry, and associated in these with a copper chloride, possibly atacamite).

The deposits with payable copper-ore take many widely differing forms, as follows:—

Deposits in limestone and shale, not connected with fissure-veins.
- Irregular bodies near contacts of main stock or dikes.
- Tabular bodies near contacts of main stock or dikes following stratification.
- Tabular bodies, following contacts of porphyry dike (all of these carry oxidized ores, almost exclusively; rarely chalcocite).

Fissure-veins.
- Normal veins in porphyry or in any of the other rocks near porphyry-contacts. Include central veins and surrounding partly-replaced porphyry forming together a lode. Carry chalcocite as the important ore; in upper levels also sometimes oxidized ores.
- Normal veins, following porphyry dikes in granite. Chalcocite and oxidized copper-ores.
- Normal veins following diabase-dikes. Chalcocite and oxidized copper-ores.

Stock-werks. Irregular disseminations in porphyry, quartzite and other rocks. Contain chalcocite and oxidized copper-ores.

The above classification is based on occurrence and form, and a more general genetic system, given below, shows a somewhat different arrangement.

Native copper, all of the oxy-salts of copper, and chalcocite are wholly secondary minerals produced by direct or indirect oxidation from primary pyritic ores. In all of the divisions given above, this primary ore consists of pyrite and chalcopyrite, with some zinc-blende and molybdenite. The scant gangue of the veins consists of quartz, while the deposits in

the first division are usually accompanied by garnet, epidote, magnetite, diopside, tremolite, or their products of oxidation.

Metamorphic Processes.

The region described in this paper is practically unaffected by regional or dynamic metamorphism, and even the ordinary hydro-metamorphism has altered the rocks but little, producing some slight changes in granite and porphyry and introducing cherts into the limestones. Epidote, chlorite, and a little pyrite are apt to develop in the hornblendic phases of the porphyry.

Contact-Metamorphism.

Contacts of porphyry with sedimentary rocks often show typical instances of this metamorphism. The granite-porphyry and the quartz-monzonite porphyry show themselves most effective in this direction, while there is usually but little metamorphic action at the contacts of the diorite-porphyry. The effect seems in direct proportion to the amount of quartz contained in the porphyry. Granite and quartzite are unaltered; the shales and sandstones of the Cretaceous series are hardened and baked. The shales change, as a rule, only at the immediate contact, to dense, greenish hornfels.

The Paleozoic limestone-series comes in contact with the main stock in two places—at Morenci and at Metcalf. In both places extensive copper-deposits are encountered. Dikes also occur at both places and along some of these radiating out into the unaltered areas the metamorphic processes may be examined to best advantage.

In studying the phenomena along dikes, it is found that the metamorphism varies greatly in the different strata, and even in apparently similar limestone layers there may be great difference in the degree of alteration. A well-defined dike 50 ft. wide on Modoc mountain was studied with special care as it cut through all of the formations present. Where contained in the Longfellow limestone the metamorphism extends at most 20 ft. outward into the limestone, and generally only a few feet. Garnet, epidote, diopside, specularite, and magnetite are the minerals which form abundantly by metasomatic replacement along the contacts, and intergrown with them are chalcopyrite, pyrite, and zinc-blende, unquestionably of contemporaneous

formation. The contact metamorphic limestone has certainly a very different composition from the unaltered rock, and it is apparent that much silica, iron, copper and zinc, at least, have been added. Epidote often forms in considerable quantities close to the contacts, while a little farther away garnet prevails. The Morenci shales overlying the Longfellow limestone are hardened and baked, but not materially altered in composition. Finally, when the dike enters the pure limestone of the Modoc formation, garnet forms in enormous quantities from the latter; the metamorphism exerted by the dike here merges into that affecting the whole block of limestone, due to the contact of the main stock of porphyry.

The principal metamorphic area at Morenci is about 2 miles long; its width is from 1,000 to 1,500 feet. The Modoc formation, however, has been affected to an extraordinary degree, and extends as a stratum of garnet and magnetite 2,000 ft. distant from the contact between almost unaltered Devonian and Cretaceous sediments.

The Longfellow limestone, though somewhat irregularly altered, is, next to the contact, generally transformed into a coarsely granular rock of garnet, epidote, diopside, magnetite, pyrite, zinc-blende, and chalcopyrite, and there is a most decided change of composition, chiefly consisting in additions of silica and iron. Other parts are less altered, but contain much magnetite, together with the sulphides mentioned, disseminated through a medium-grained crystalline mass of the carbonates of lime and magnesia. The development of magnetite, metasomatically, is a most pronounced feature of the process. Looking at the formation as a whole; sulphur, iron, copper and zinc have certainly been added, and probably also silica and magnesia. Large masses of magnetite, locally used as a flux, have been mined at this horizon.

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shared by myself and expressed in a recent paper on contact-metamorphic deposits.[6]

The truth seems to be that in many cases no perceptible accession of substance from the magma has taken place, while perhaps, equally often, important additions have been received. How far the heat and the gases from the intruded magma will penetrate, and what effects they will produce, depend on many factors. As shown above, the composition of the magma is sometimes a factor of importance. In case of the Morenci contact-zone, the quantity of substance available seems to stand in direct relation to the quantity of quartz in the porphyry. In many intrusive magmas there may be a very small quantity of water present; the access of material may then be slight and the contact-phenomena mostly due to the heat of the rock. The difference in susceptibility of the various beds is also strongly marked; all investigators agree on this point. In this district impure and very compact limestones resist alteration much more than coarse-grained pure rocks of the same kind; and the change in composition in the case of clay-shales is extremely slight.

Study of the Morenci contact-zone, as a whole, proves conclusively that most important accessions of substance have been received. The rocks inside of the altered zone contain an enormous quantity of sulphur, iron, copper, and zinc. Iron is, of course, contained in the unaltered rocks to some slight extent, but in nothing like the quantities accumulated in the contact-zone; sulphur, copper and zinc in noticeable amounts are absent from the unaltered rocks. Were they present, to the extent of a small fraction of the percentage contained in the contact-zone, they could be detected, either directly or through the products of their surface-oxidation. The minerals in which these substances are contained were certainly formed contemporaneously with the ordinary contact-minerals of the district, like garnet, diopside and epidote.

The metasomatic development of magnetite in pure limestones which has recently been questioned by Prof. Klockmann may be observed in almost countless localities at Morenci and Metcalf, both in the field and under the microscope. It is

[6] *Trans.*, xxxi., 226–244 (1901) and *The Genesis of Ore-Deposits*, p. 716, 2d ed. (1902).

known that iron was not contained to this extent in the original rock, but to demonstrate its actual derivation in each case is, of course, difficult. The question becomes clear only when we compare the contact-zone as a whole with the original unaltered rocks.[7]

It seems very strange that any one can doubt the possibility of such additions, and overlook what must happen when a magma in aqueous fusion is suddenly brought up to higher levels and strongly ionized water-gas above the critical temperature is largely released from its bonds. It must of necessity contain dissolved substances. Even at comparatively low temperatures water is one of the most powerful solvents known, and its action, when a perfect gas, is probably far in excess of that at 100° or 200° C. It is well known that some rapidly congealed rocks, like the "pitch stone" from Saxony, contain up to 8 per cent. of water, indicating an amount of water-gas which, per cubic meter of magma, would at + 4° C. correspond to from 250 to 300 liters.[8] All magmas may, of course, not have contained this amount. The water-gas seems to have penetrated the limestones like a sponge, inducing extreme molecular mobility. Even should we deny any additions of substance, a most remarkable transferring of substance has certainly taken place in the rock, as shown, for instance, by large crystals of garnet developing in limestones of uniform

[7] Professor Klockmann's article, which is really intended to prove that no important deposits of magnetite can have a contact-metamorphic origin and that no important material can be transferred from cooling-magmas to adjoining sediments, was published in *Zeitschrift für Praktische Geologie*, vol. xii., p. 78 (1904). Among the arguments used is one referring to the content of alumina in epidote, and to the improbability of transfer of that metal from magma to limestone. At Morenci the massive epidote is usually confined to the immediate vicinity of the contacts, and I fully believe that some transfer of alumina has actually occurred. Regarding the occurrence of that mineral within the contact-metamorphic zone, but at some distance from the actual contact, it is not likely that the alumina represents an addition from the magma, but it is certain that under the peculiar conditions obtaining during the metamorphism the alumina to no small degree shared in that wonderful molecular mobility which characterized the whole process.

When, however, Prof. Klockmann refers to garnet as an essentially aluminous mineral, a typographical error must surely have occurred. All garnets do not contain alumina, and the contact-metamorphic garnets at Morenci and Metcalf are throughout andradites or lime-iron garnets.

[8] E. Weinschenk, Vergleichende Studien ueber den Kontakt-Metamorphismus, *Zeitschrift der deutschen Geologischen Gesellschaft*, vol. liv., p. 443 (1902).

composition containing far less iron and silica than the amounts required by the newly-formed mineral. In a chapter on inclusions cogent proof will be brought that the magma actually was accompanied by water that contained a large amount of substances in solution.

A misapprehension of the character of contact-deposits seems to exist in many quarters, as shown, for instance, by Prof. Klockmann,[9] in considering the presence of minerals containing boron, fluorine, etc., as necessary to prove the contact-metamorphic character of these deposits. To such arguments I would reply that the character of magmatic waters evidently varies greatly in different magmas. Some may carry large quantities of the substances mentioned, as shown by the presence of tourmaline, cassiterite and other minerals in the contact-metamorphic rocks, while others may be almost wholly deficient in them, and, instead, carry sulphur, copper, iron, and other metals. In the Clifton group of deposits, I would be inclined to consider molybdenum a characteristic constituent, taking the place of tungsten in the tin-deposits. Any attempt to reduce the wonderful variety in the contact-metamorphic deposits to a single pattern is doomed to failure.

In a short paper dealing with contact-metamorphic deposits in North America,[10] I emphasized the irregular form of most ore-deposits of this kind and declared that they only occur close to the contact or, at most, a hundred feet away. As a result of wider observations I would modify this statement; as far as we know at present, they may occur several hundred or even 2,000 ft. away from the contact. In fact, disseminated sulphides and magnetite occur at Morenci as far as 2,000 ft. from the main contact.

A tabular form of deposits often noted is usually due to the strongly marked difference in susceptibility of the various beds. Wherever the deposits have been enriched by oxidation the form may be more or less dependent upon these changes.

Mr. W. H. Weed has noted the tabular shape in contact-deposits at Cananea, Mexico, and makes the form a basis of classification.[11] I do not believe, however, that distance from

[9] *Zeitschrift für Praktische Geologie*, vol. xii., p. 75.

[10] *Trans.*, xxxi., 226 (1901).

[11] Ore-Deposits near Igneous Contacts, p. 364, this volume.

contact (within limits given above) and shape are at all essential, and can find no mineralogical difference between deposits varying in these respects.

Hydrothermal Metamorphism.

Both the porphyry- and the contact-zone are traversed by fissure-veins which carry pyrite with a small quantity of chalcopyrite, zinc-blende and molybdenite, whenever oxidation has not changed these minerals. These pyritic veins are of low—generally unpayable—tenor; they consist of prevailingly granular or massive, very rarely crustified, minerals with a little quartz-gangue, and are believed to have been formed by pyritic replacement along well-defined fissure-planes. In the porphyry these veins are surrounded by very wide zones in which the rock is greatly altered by the introduction of sericite and pyrite, and this applies to Metcalf as well as to Morenci. At the latter place almost the whole of Copper mountain, containing the most important lodes, is thus altered. The process which, in my complete report, is elucidated by many analyses, produces bleached rocks of varying hardness in which all of the feldspar has been replaced by sericite and some pyrite. The biotite and hornblende are transformed into chlorite and serpentine, while the silica of the rock remains almost constant. All of the lime and soda is eliminated, while potash is greatly increased. No carbonates are formed during this process.

Little alteration is noted where fissure-veins cut through contact-metamorphic shale, nor when highly altered garnet-magnetite rock forms the walls, but in unaltered or slightly metamorphosed limestone a change is observed, For a short distance from the vein—a few inches or a few feet—the rock is bleached and proves to have been converted into tremolite, more rarely diopside, with disseminated pyrite, chalcopyrite, and zinc-blende, all more or less intimately intergrown with magnetite. This alteration involves a loss of carbon dioxide and some lime, as well as addition of silica, iron, magnesia, and the sulphides mentioned above. More rarely argillaceous limestones are altered to sericitic minerals with magnetite and sulphides. Magnetite has not been observed in the massive pyritic veins, although it occurs in the altered country-rock.

Relation of Contact and Hydrothermal Metamorphism.

The alteration of limestone along fissure-veins to tremolite (or diopside) with magnetite and sulphide is, so far as I know, a novel one. Ordinarily, limestone alters next to fissure-veins to dolomite or quartz or jasperoids.[12] The addition of silica and iron and the mineralogical trend of the hydrothermal process at Morenci undoubtedly connects it in some way with contact-metamorphism, making it probable that the alteration took place at high temperature comparatively soon after the solidification of the porphyry.

At first glance, it might seem plausible to assign all the changes which have taken place in the metamorphic zone to the same hydrothermal alteration which has affected the porphyry along the fissure-veins. This view, however tempting, is surely incorrect. Instead of one set of phenomena, there are two related and, in part, superimposed processes. Among the proofs of this are the absence of sericitization in the porphyry of many dikes which have exerted strong contact-metamorphism. Further, the entire independence which the masses of extremely altered garnet-magnetite rock show in regard to the fissure-veins, and their distinct dependence on contact of dikes and main stock. The vein-alteration produces dull, earthy rocks from the limestone, while contact-metamorphism results in hard, compact and granular rocks. On the other hand, there is undoubtedly a certain relation between the two processes for amphibole (and pyroxene) occurs in the true contact-metamorphic rocks, and the intergrowth of magnetite and pyrite is characteristic of both. I should, therefore, conclude that after the completion of the contact-metamorphism, properly speaking, and after the consolidation of the porphyry, an extensive fissuring took place and solutions derived from the cooling porphyry, probably ascending and laterally extending from this rock, flowed through these fissures. Everything indicates that these solutions were closely related to those which emanated from the magma at the moment of intrusion and, in fact, similar in general composition.

As to the quantitative relation of contact-metamorphism and hydrothermal metamorphism, it is difficult to speak with ab-

[12] W. Lindgren, Metasomatic Processes in Fissure-Veins, *Trans.*, xxx., 578 to 692.

solute certainty. In some parts of the contact-metamorphic rocks small seams with sulphides and magnetite are very abundant (for instance, in the Yavapai mine) and it is not easy to say how much of this should be credited to each form of alteration, for the sedimentary rocks were evidently solid during the intrusion, and seams filled with sulphides may well have formed in them. Generally speaking, they would be, and, in fact, are at present much less permeable to solutions than the porphyry, as shown by the slight depth which oxidation has attained in them, and it is believed that the hydrothermal solutions were chiefly confined to cracks and fissures in contradistinction to the much more searching action of gaseous water. The facts above given show indeed how slight is the lateral spread of alteration from the veins in limestone. That the solutions producing the contact-metamorphism effected such intense results is probably due to the existence of a far greater degree of heat and gas-pressure.

Processes Due to Oxidation and Hydration in the Altered Zone.

Under influence of surface-waters (but protected from direct oxidation), chlorite and serpentine form from the tremolite and diopside of the contact-zones, while garnet is little altered. Under direct oxidizing-action, garnet changes to limonite and quartz, while lime is probably carried away as carbonate. Tremolite and related minerals are similarly affected. Magnetite oxidizes to hematite and limonite, many large bodies of which are mined for fluxing-purposes. Pyrite changes by direct oxidation into ferrous sulphate and free sulphuric acid; the ferrous sulphate upon further oxidation yields ferric sulphate and the latter is easily decomposed into basic sulphates, ferric hydrates and free acid; ferric sulphate is also ready to attack pyrite and other sulphides, changing them to sulphates and being itself reduced to ferrous sulphate.

This cycle of reactions will finally transform all of the sulphides present into various, more or less soluble, oxy-salts. A large part of the pyrite will be changed to limonite. Such "iron caps" are seen at the outcrops of many veins in regions where oxidation proceeds undisturbed by erosion, but in this region they are generally absent.

The veins are marked by siliceous outcrops, either entirely

barren or containing small amounts of oxidized copper-ores. No basic ferric sulphates have been seen either in the mines or on the surface. The waters percolating downwards must soon have lost their oxygen and, for the alteration at greater depths, ferrous sulphate and diluted sulphuric acid are probably the only reagents of importance resulting from the pyrite. It is clear that the upper part of the veins have not been formed by simple oxidation of pyrite and accumulation of limonite.

Direct oxidation of chalcopyrite yields cupric and ferrous sulphates, while the zinc-blende produces zinc sulphate; both of these processes are in evidence wherever the disseminated sulphides in the metamorphic rocks are exposed to oxidation. The general order of attack of oxygen is usually stated as follows:—Arsenopyrite (most easily attacked), pyrite, chalcopyrite, blende, galena and, finally, chalcocite (most difficultly attacked). This rule is probably true only for one set of conditions as to mass, aggregate and character of solutions. Very marked exceptions from it occur at Morenci.

Sulphate Waters.—Descending-waters from a lode of decomposing pyrite, chalcopyrite and zinc-blende should contain chiefly ferrous, cupric and zinc sulphates, together with free sulphuric acid. The first two salts are easily soluble, but far more so is the zinc sulphate.

Cuprous sulphate is stable only under certain conditions and is not believed to be an important reagent, though it may form during subsidiary or intermediate reactions. Its presence in any mine-waters has not been satisfactorily proved.

In this district, some moisture percolates the upper workings, as shown by efflorescences and stalactites of sulphates, but the mines are practically dry. In the porous porphyry the moisture spreads easily, while the hard metamorphic rocks offer considerable resistance.

Processes in Fissure-Veins.—Below the region of oxidizing-influences the veins consist of pyrite, chalcopyrite and zinc-blende, while the upper few hundred feet contain chalcocite and oxidized copper-ores. The most important action of the descending sulphate solutions has been a development of chalcocite by the action of cupric sulphate on primary pyrite-ore; this process began at the time the veins were first touched by

oxidizing waters, and continues to some extent to the present time.

If secondary deposition of sulphides has taken place according to Schuermann's reactions, they should be arranged in the upper zones of the deposit in the following order:—(*Top*), galena, zinc-blende, chalcocite, bornite, chalcopyrite and pyrite. (*Bottom.*)

In Morenci, practically only chalcocite thus forms. The first of the primary minerals attacked is the zinc-blende which appears to be rapidly transformed, first into covellite and then into chalcocite, as follows:

$$ZnS + CuSO_4 = ZnSO_4 + CuS.$$

Chalcopyrite, present only in small quantities, is probably attacked at the same time. The zinc sulphate is carried away and no zinc minerals appear in the upper, oxidized part of the veins.

Contrary to the list just given above, blende is thus attacked before the pyrite. The conversion of pyrite to chalcocite may be studied in all stages of the process; it is a molecular replacement attacking the pyrite from cracks and fissures, and gradually eliminating it entirely. However, even in the best chalcocite-ores residual pyritic cores ordinarily remain. Dr. Stokes has shown that the reaction at + 100° C. and + 200° C. proceeds as follows:

$5\,FeS_2 + 14\,CuSO_4 + 12\,H_2O = 7\,Cu_2S + 5\,FeSO_4 + 9\,H_2SO_4 + 3\,H_2SO_4$, the last H_2SO_4 being formed by oxidation of the sulphur of FeS_2. It is probable that the reaction likewise goes on, though more slowly, between + 100° C. and + 20° C., the range probably existing in the deposit during the period of oxidation. Mr. H. V. Winchell's reaction[13] necessitates sulphurous acid as a reagent, the presence of which seems unlikely. The equations given by Prof. Van Hise[14] for the formation of secondary copper sulphides seem improbable, as they require

[13] Synthesis of Chalcocite and Its Genesis at Butte, Montana, *Bulletin of the Geological Society of America*, vol. xiv., pp. 269-276.

[14] Some Principles Controlling the Deposition of Ores, *Trans.*, xxx., 101, 111, 112.

the presence of free oxygen, and as they are generally based on cuprous sulphate.

By this process of alteration the massive pyritic veins have been transformed into almost solid, dull, sooty chalcocite; and the zones of dissemination surrounding them in the porphyry have changed into low-grade chalcocite-ores. The process is accompanied by the formation of some kaolin, quartz, chalcedony, and probably also opal. No sericite forms. The kaolin develops metasomatically at the expense of the sericite, and sulphuric acid was evidently the reagent. Alunite is in places formed in the same manner. Extremely large amounts of ferrous sulphate must have been carried away during this process.

Oxidation of Chalcocite.—After a large part of the chalcocite in the lode had been formed, there came a time when erosion and degradation, working faster than oxidation, began to expose the upper part of the chalcocite-zone to active and direct attack by oxygen. Practically all of the veins are in this stage. The present zones of active oxidation are therefore due, not to direct oxidation of the primary lode, but to the destruction of the upper horizon of the chalcocite-zone. As reagents, there are here ferrous sulphate, sulphuric acid, cupric sulphate and free oxygen. Any ferric sulphate present would soon be reduced to ferrous salt by the abundant pyrite. Chalcocite changes to cuprite and cupric sulphate, sometimes with an intermediate stage of covellite.

$$2\,Cu_2S + O = 2\,CuS + Cu_2O \text{ and } CuS + 4O = CuSO_4.$$

Cuprite partly reduced to metallic copper is, in fact, abundantly present in the upper limit of the chalcocite-zone.

$$Cu_2O + H_2SO_4 = Cu + CuSO_4 + H_2O.$$

By some process not quite elucidated, chalcocite may, in places, change directly into native copper. The zone of cuprite and metallic copper has rarely great vertical extension, for the reason that both minerals are rapidly converted into cupric sulphate, brochantite, malachite, azurite and chrysocolla; but these products are soon dissolved by free sulphuric acid from pyrite, a mineral which tenaciously remains until the last, and descend

as soluble sulphates to enrich the upper part of the chalcocite zone.

In the Copper Mountain veins, contained in porphyry, oxidized copper-minerals are almost entirely absent, probably because of the great amount of free sulphuric acid present. The chalcocite disappears at from 100 or 200 ft. below the surface, and the lode consists of a rusty mass of sericitized porphyry, with considerable amounts of remaining pyrite and efflorescences of cupric sulphate. The last particles of pyrite only disappear close to the surface.

In places, chalcocite may change directly into brochantite or malachite. Cupric oxide (melaconite or tenorite) has not been found.

Oxidizing Processes in Limestone.—The processes which have resulted in the oxidized deposits now forming irregular or tabular masses in limestone or shale, and not connected with fissures, are materially different from those occurring in the lodes. In most cases the original material consisted of disseminated lean pyritic ores, containing pyrite, chalcopyrite, zinc-blende, and magnetite, locally more or less concentrated in irregular masses, or following certain strata- or dike-contacts. Free oxygen and sulphuric acid, ferrous and cupric sulphates, with an abundance of calcium carbonate, formed the reagents. Though oxygen and carbon dioxide may in part have produced limonite and malachite directly from pyrite and chalcopyrite, the most important reactions doubtless were those between calcium carbonate and sulphate solutions, partly derived from nearer the surface.

$$2\,CuSO_4 + 2\,CaCO_3 + H_2O = (CuOH)_2, CO_3, + 2\,CaSO_4 + CO_2 + H_2SO_4.$$

$$3\,CuSO_4 + 3\,CaCO_3 + H_2O = (CuOH)_2, Cu\,(CO_3)_2 + 3\,CaSO_4 + CO_2.$$

In the first case malachite, in the second azurite forms, together with gypsum. The latter mineral, though largely carried away in solutions, is not uncommon in these deposits at Morenci. Ferric hydrate will be produced from ferrous sulphate and calcium carbonate. Thus, in general, is explained the constant occurrence in these deposits of malachite, azurite

and limonite. Crusts of replacing-malachite and azurite frequently surround residual, rounded masses of limestone. The gangue of garnet and magnetite alters to ferric hydrate and quartz. Chrysocolla forms when silica is plentiful; zinc-minerals are not uncommon in these deposits, and efflorescences of the zinc and magnesia sulphates sometimes cover the tunnel-walls. During the process outlined above, lime is almost wholly eliminated, while alumina forms residual concentrations.

Oxidizing Processes in Shale.—Disseminated cuprite in beds of Morenci shale is a common occurrence, and some of the large ore-bodies of the Manganese Blue mine were of this character. It occurs as flakes on the bedding-planes, or in small replacement-veins, sometimes accompanied by distinctly-later malachite and by limonite. These occurrences seemed difficult to explain, but light is thrown on them by recent experiments by Dr. E. Kohler,[15] who shows that solutions of cupric sulphate, filtered through kaolin, become hydrolyzed by adsorption. The copper is precipitated as oxide, and sulphuric acid is set free. (Experiments are now in progress which seem to indicate that the Morenci shale possesses remarkable power of adsorbing copper from aqueous solutions.)

Azurite also occurs frequently in shale, as shown by the second ore-body in the Detroit mine. Large crystals of that mineral develop here, metasomatically, in a metamorphic shale composed of sericite and amphibole. Cases have been observed where azurite envelops masses of undecomposed pyrite accompanied by a little limonite. During the oxidizing process the alumina possesses considerable mobility. It is dissolved by sulphuric acid from clay-shale and forms certain aluminous minerals, notably sericite. The aluminium sulphate formed is extremely soluble in water, and thus easily transported. At many places in the mines of Morenci, pure kaolin forms, together with azurite and malachite.

Paragenesis.

The minerals formed during successive stages are as follows:

[15] Adsorptionsprozesse als Faktoren der Lagerstättenbildung und Lithogenesis, *Zeitschrift für praktische Geologie*, vol. xi., p. 49 (1903).

VEINS.	
Primary Processes.	Pyrite, chalcopyrite, zinc-blende, molybdenite (rarely magnetite), sericite, quartz, rarely tremolite, diopside and epidote. Introduction of iron, sulphur, zinc, copper, molybdenum, potassium and silica. Elimination of calcium and sodium.
Processes of Oxidation.	
Action of sulphate solutions without oxygen.	Chalcocite (rarely covellite, chalcopyrite, and bornite), quartz, chalcedony, kaolin, alunite. Introduction of copper. Elimination of zinc, some iron and sulphur.
Action of directly oxidizing solutions.	Cuprite, native copper, brochantite, malachite, chrysocolla (rarely azurite), chalchanthite, limonite, quartz. Introduction of carbon dioxide. Elimination of sulphur, together with some iron and copper.
CONTACT-DEPOSITS.	
Primary Processes.	Pyrite, magnetite, chalcopyrite, zinc-blende, molybdenite, specularite, garnet, epidote, diopside, tremolite, quartz. Introduction of much iron and silica, together with copper, zinc, molybdenum, sulphur, possibly magnesia. Elimination of carbon dioxide and probably some lime.
Processes of Oxidation.	Limonite, malachite, azurite, cuprite, rarely native copper and chalcocite, copper-pitch ore, chrysocolla, goslarite, zinc carbonate, willemite, calamine, pyrolusite, quartz, calcite, chlorite, serpentine. Introduction of carbon dioxide and additional copper. Elimination of calcium, sulphur, some zinc and iron.

CHARACTERISTICS OF DEPOSITS.

Deposits of Carbonates and Oxides in Limestone and Shale.

The important occurrences of these ore-bodies are found in the Longfellow, Manganese Blue, Detroit, Copper Mountain, Montezuma, and Shannon mines.

They contain practically all of the oxy-salts of copper known from the district; but chiefly malachite, azurite and cuprite, with very subordinate amounts of native copper and chalcocite. The accompanying minerals consist of limonite, manganese peroxide, kaolin, and soft, yellowish material which, in a large proportion of deposits, generally proves to be decompos-

ing and hydrated forms of tremolite, diopside, garnet, or epidote. Some deposits of chrysocolla and limonite occur, however, in unaltered limestone, and the cuprite-bearing shales are not accompanied by any gangue except a little limonite. The copper-minerals are sometimes formed by crustification, but replacements in shale or lime are almost equally common.

The form is sometimes wholly irregular, but there is a marked tendency towards a tabular form following certain strata evidently favorable for deposition. The horizontal extent varies greatly, but rarely exceeds 300 or 400 ft., and the two dimensions are apt to be approximately equal. The thickness ranges from 1 to 30 ft. and is sometimes more. Regular boundaries rarely occur, and the pay-ore easily shades off into the country-rock. In the Manganese Blue and the Detroit mines several superimposed ore-bearing horizons are found within 300 ft. of the surface. The Longfellow deposit has the form of an inverted pyramid.

Acidic porphyry is found in the immediate vicinity of all deposits. Some of them immediately adjoin the contact of the main stock, but others show decided dependence upon dikes of porphyry; one class of deposits forms tabular masses along the contacts of dikes; others, such as the Detroit, the Manganese Blue, and the Longfellow, lie between two or three porphyry dikes, the latter being largely barren, except for some disseminated chalcocite. Fissures antedating the oxidation, but subsequent to the contact-metamorphism, have sometimes influenced the form by guiding the descending waters.

The deposits may be found in any of the Paleozoic horizons between the Coronado quartzite and the Cretaceous beds. They frequently crop at the surface, azurite appearing to resist decomposition quite obstinately.

Driving laterally, or sinking deeper from these ore-bodies, is apt to develop hard limestone with typical contact-metamorphic minerals and scattered pyritic ores. The very confident conclusion has been drawn that the majority of these deposits have been formed by the oxidation of irregular or tabular masses of low-grade pyritic ores, such as the lower mine-workings have disclosed in such abundance, for instance, in the Yavapai mine.

An enrichment accompanied the oxidation, both on account

of reduction in volume and introduction of additional copper as sulphate. The oxidation does not reach the water-level which is far below the present workings, but acts most irregularly, sometimes leaving fresh metamorphic limestone near the surface and again penetrating along fissures to a depth of 400 feet.

The above explanation does not fit all of these deposits, for some are unaccompanied by evidence of contact-metamorphism and have probably primarily been formed by the action of thermal, vein-forming waters, and others are entirely of secondary origin, being deposited in shales and in the clays along important faults by migrating sulphate solutions. The oxidation of the present ore-bodies followed the faulting movement and probably began at a rather early epoch of Tertiary times.

Fissure-Veins and Related Deposits of Morenci Type.

Fissure-veins with a northeasterly or northerly trend, but of no great individual length, follow the entire length of the porphyry stock, but are especially developed between Morenci and Metcalf and on Copper King mountain. The most prominent lode system at Morenci extends for about 2 miles, and consists of a number of shorter-linked and branching fissures, forming two belts slightly curved towards the southeast. One of them lies in porphyry within a few hundred feet of the contact and comprises the principal mines of the district—the West Yankee, the Humboldt, and the Copper Mountain. The other and parallel system traverses the metamorphic rocks a few hundred feet southeast of the contact.

The dip is steep to the NW. or SE. and the system is thus a conjugated one, bearing every evidence of origin by compressive stress.

Outcrops are very poor, frequently wholly unrecognizable, and it is most difficult to trace the veins on the surface. Low-grade malachite, chrysocolla, and brochantite-ores are contained in the outcrops of some veins. Large masses of limonite while common enough in the oxidized contact-metamorphic deposits do not usually occur in the vein-croppings.

Underground exposures always show one or more well-defined walls frequently polished and striated. The faulting-movement on these fissures is slight.

In the majority of these deposits there is a central vein which ordinarily is 4 ft. wide or less, but may sometimes expand to 50 ft.; it is composed of nearly massive sulphides, and closely follows the fissure. In the porphyry, this is surrounded by a much wider zone of altered rock which may constitute ore; the central vein and the altered zone together are characterized as a "lode." In almost all of the veins the following vertical distribution of ores is noted:

Surface Zone.	From 50 to 200 ft. deep from the croppings. Contains oxidized copper-minerals or is barren.
Chalcocite Zone.	From 100 to 400 ft. in vertical extent; possibly more in places. Contains chalcocite and pyrite.
Pyritic Zone.	Begins from 200 to 600 ft. below the surface. Contains pyrite, chalcopyrite and zinc-blende.

It has been shown that the minerals of the two upper zones have been derived from those of the pyritic zone by processes of direct and indirect oxidation; that the chalcocite is wholly formed by replacement of pyrite effected by solutions of cupric sulphate; that secondary covellite, chalcopyrite and bornite only occur in very small amounts. Also, that the surface-zone is derived from the chalcocite-zone by its direct oxidation. It has further been emphasized that the pyritic zone is generally very poor; that the chalcocite-zone produces the richest ore, and that the surface-zone is always poor and sometimes barren.

The pyritic part of the veins is, with good reason, believed to represent the primary deposition of sulphides along the fissures. It contains a small amount of quartz-gangue with intimately intergrown pyrite, zinc-blende and chalcopyrite; the two last-named minerals are present only in small quantities; molybdenite also occurs. A well-defined foot-wall is usually present, while the hanging-wall may be more or less indistinct or represented by several subordinate fissures. The deposition seems to have been chiefly effected by metasomatic replacement of crushed and sheeted porphyry, or metamorphic rock. The zone of altered rock surrounding the vein consists of sericitized and pyritic porphyry when the vein is in this rock, and may then be very wide. In the hard, metamorphic limestone and shale, this zone is narrow and shows either an amphibolitic or a sericitic alteration and contains besides pyrite, chal-

copyrite and zinc-blende intergrown with magnetite, a mineral absent from the vein proper. In the chalcocite-zone, commercially the most important, magnetite has largely, but rarely wholly, replaced the pyrite, both in the massive veins and in the zones of pyritization and sericitization surrounding them at a certain depth. It is generally sharply separated from the pyritic zone, the transition taking place within a surprisingly short distance. Below this limit, evidence of chalcocitization can only be found along fissure-planes. The uppermost part of the chalcocite-zone is invariably the richest. The massive pyrite veins form pure, dull black chalcocite, or a mixture of pyrite and chalcocite. This constitutes high-grade ore with more than 5 per cent. of copper—ranging up to 70 per cent.—while the pyritized porphyry turns into low-grade ores with from 2 to 5 per cent. of copper.

To these large bodies of low-grade ore the recent great development of the district is due. In some mines, which are generally on the lower slopes, or in the bottoms of canyons, the chalcocite begins almost at the surface. At Morenci, situated high up on the hills, the depth from the surface is rarely less than 200 ft. The depth on the vein attained by the chalcocite-zone, from the level where direct oxidation begins to the upper limit of the pyrite-zone, varies greatly; it is sometimes less than 100 ft., while under Copper mountain the average would somewhat exceed 200 ft. Directly below the summit it is 300 ft., and its lower limit in some cases has not yet been reached. In general, the upper limit would be represented by a curved line somewhat less convex than the contours of the mountain. The lower limit seems to be flatter, but great irregularities exist, due no doubt to exceptional conditions of circulation of surface-waters.

The great bodies of low-grade ore are almost wholly confined to the lodes in porphyry; and the pay-zone generally contracts greatly when contact-metamorphic shales or limestones are entered. Stopes of low-grade ore range from a few feet to 100 ft. or more in width; many are 200 ft. long and have been stoped for the same vertical distance. The great body of concentrating ore between the two Humboldt walls, which dip against each other, is about 300 ft. long, up to 200 ft. wide, and has been stoped 200 ft. high. Values gradually

decrease on both sides unless, as sometimes happens, cut off by fissures on one or both sides. The limit is thus usually simply determined by the lowest grade of ore workable. Sericitization and chalcocitization has spread considerably farther, laterally, than is indicated by the 2.5 or 3 per cent. of copper contained in the lowest grade of ore mined.

The ore-shoots of Copper mountain are thus materially different from those usually found in gold- and silver-veins. Their greatest extent is horizontal rather than vertical, and their size depends more upon conditions of circulation of surface-waters than upon the primary distribution of copper in the vein. Prospecting for reserves must proceed laterally rather than towards extreme depth.

The surface-zone is always richest near the lowest limit of oxidation where cuprite and native copper form from chalcocite. The upper part contains poorer ores of malachite, brochantite, etc., and may be entirely barren.

In the Copper Mountain veins the chalcocite apparently changes directly to cupric sulphate; and other copper oxy-salts are practically absent. The pyrite remains, in part, rusty and accompanied by limonite, until near the surface, where it finally disappears. The surface-zone is thus directly derived from the chalcocite-zone by gradual erosion and oxidation, indicating that the latter is not a very recent development.

Two of the principal faults of the district cut across the Morenci veins and dislocate them. Some of the ore-bodies are clearly faulted, so that rich chalcocite-ore is brought opposite leached and barren surface-rock. Brecciated zones, accompanying this faulting, contain fragments of chalcocite-ore. In all, the evidence is pretty clear that, at least a part of the chalcocite-zone had already been formed when the faulting took place, and that, consequently, the beginning of chalcocitization and oxidation must be placed in the earlier or middle part of Tertiary times.

Descriptions of chalcocite-ores from other districts show that the secondary sulphides develop at a point just below the water-level. In none of the important mines in this district has the water-level been reached; it is probably far below the present workings. Chalcocite may now form in the upper part of the zone, in places away from fissures and faults, where

sulphate solutions are slowly descending and free oxygen scarce, but I doubt very much whether it is now forming in the lower part of that zone. I regard the chalcocite-zone as formed about an ancient, gradually-receding water-level. During the early Quaternary, that level was evidently several hundred feet higher than at present, but the occurrences of the chalcocite appear to require a still higher stand, such as existed during the probably moist climate of the middle Tertiary.

The payable deposits, as a rule, lie at high elevations, and no large deposits have been opened on the lower slopes of Chase Creek canyon, or along its bottom. The lower down on the slope a deposit is located, the nearer to the surface will the chalcocite-zone be found. Chalcocite-ores do occur, in fact, in veins along the bottom of Chase Creek canyon, but the mineral shows only as a slight coating on pyrite. This topographical distribution is the more remarkable when it is recalled that Chase Creek canyon antedates the early Quaternary conglomerates (Gila formation) and that, therefore, oxidation would apparently have had a long time in which to act. It confirms the conclusions as to the great age of the chalcocite-zone and emphasizes the very slow rate at which oxidation works.

Chalcocite-ores and oxidized ores forming a "stock-werk" of seams in porphyry (at Metcalf mines), or in quartzite (at the East Yankee mine), or occurring as disseminations in porphyry dikes (West Yankee lode and Shannon mine), in general correspond to the descriptions of the altered zones surrounding the veins. They pre-suppose an earlier sericitization and pyritization effected by the primary vein-forming solutions.

The fault-planes of the principal epoch of dislocations are later than the Morenci veins and generally barren, but may locally contain "drag" or cuprite-ores deposited from migrating sulphate solutions by processes of adsorption.

The Coronado Type of Veins.

Almost the only representative of the Coronado type of veins is the Coronado lode, which outcrops on the summit of Coronado ridge about 2,000 ft. above Metcalf. It presents the feature unusual for a fissure-vein of following one of the principal faults of the district with a throw ranging from 1,000 to 2,000 ft., and it is traceable for nearly 2 miles, finally disap-

pearing towards the west under the basaltic foothills of Eagle creek. The fault-zone, which is from 50 to 200 ft. wide, is followed by a diabase dike which has been crushed and partly deformed. Oxidized ores, malachite, azurite and chrysocolla, of medium to poor grade, occupy irregular shoots in the surface-zone, but are replaced at a depth of from 200 to 300 ft. by chalcocite-ores. At some points the latter, however, reach the surface. Explorations during the last two years are reported to have developed large bodies of these, even at a depth of 500 ft. below the surface. The evidence—as far as it goes—here, too, points to secondary origin of chalcocite and its derivation from pyritic ores, but here, as well as at Morenci, the maximum depth attained by the secondary chalcocite has not been fully demonstrated.

The Coronado lode was formed later than the Morenci type of veins and subsequent to the intrusion of diabase, which is younger than the porphyries of Morenci and Metcalf. Regarding the relative age of the diabase and the fault-fissure, the evidence is hardly conclusive. It seems as if the dike had been intruded during the epoch of faulting, and the solutions depositing the copper certainly followed the intrusion of the dike.

Gold-Bearing Veins.

Gold, silver and lead are practically absent from the principal deposits, but it is an interesting fact that they begin to appear in many of the outlying-veins somewhat distant from the central mass of porphyry. These veins, in which copper is apt to play a less important part, have not as yet attained much importance from an economic standpoint.

Conditions of Ground-Water.

Permanent water has not thus far been encountered in any of the mines in the whole district with which this paper deals. Morenci is situated on the hills from 800 to 1,500 ft. above the principal streams, Chase creek and Eagle creek; and the deepest workings in no place reach farther than 600 ft. below the surface. A little seepage from the surface takes place in case of heavy rains, or from the local water-supply; and some drifts and cross-cuts underneath the town are somewhat damp, especially in the Manganese Blue and Arizona Central mines. The mines at

Metcalf are situated on Shannon mountain from 500 to 1,200 ft. above Chase creek, and here, too, the workings are dry, excepting one place in the Shirley tunnel where a winze struck some standing water. The few shafts and prospects, sunk in the bottom of Chase creek, are the only places containing permanent water. The Copper King mine, situated a few hundred feet below the summit of the mountain of the same name, has a shaft 600 ft. deep; some crevices containing water have been found in it, but they soon drained out and no more has since come in.

The present stand of the water-level, except along the creeks, is practically unknown. It probably rises as a slightly curved surface from the creek-levels towards the high hills. The total amount of water stored below this water-level is probably small.

Depth of Oxidized Zone.

The presence of products of direct or indirect oxidation shows the depth to which the oxidizing-waters or the sulphate solutions have penetrated; but the porphyry and the metamorphosed limestones should be separated, because they act very differently. In that part of Copper mountain which has been explored, the average depth of the lower limit of the chalcocite-zone is 400 ft., but it increases in places to 500 or even 600 ft. To this depth from the surface, the sulphate solutions descended, and along important fissures they may have gone somewhat farther. The solutions not only followed fissures, but penetrated the porous, sericitized porphyry with considerable ease. On the other hand, the altered limestones and shales are very compact, non-porous and impervious. Where circulation was facilitated by fissures, as in the Manganese Blue and the Joy mines, the rocks may be partly oxidized to a depth of 400 ft., but this is generally a maximum. There is no well-defined plane expressing the depth of oxidation, which, on the contrary, proceeds very capriciously, fresh sulphides being frequently found very close to the surface.

Fluid-Inclusions.

Fluid-inclusions have been observed in the quartz-grains of granite, quartzite, porphyry and vein-quartz occurring in this district. There is nothing uncommon in this; it is, indeed, the

ordinary condition of affairs. As these fluid-inclusions, beyond doubt, contain aqueous solutions, it may be regarded as certain that such fluids were present when the quartz-grains in question were formed. It is the purpose of the following paragraphs to call attention to certain phenomena in these inclusions which have not been described previously.

In Granite.—Inclusions, filled with a fluid and a bubble of gas, occur abundantly in the quartz-grains of all of the granites examined. They are of rare occurrence, though not unknown in the feldspars. The form is round or elliptical, or may be that of a negative quartz-crystal with prism and pyramid. The size averages perhaps 0.02 mm. The relation of volume between the fluid and the bubble varies considerably among inclusions in the same grain. In the smaller inclusions the bubble frequently is in active motion. Heated to 40° or 50° C. there is no perceptible change in volume of fluid or bubble, and consequently it may be considered certain, that the fluid is not liquid carbon dioxide, which has sometimes been observed in the granites, but chiefly water. In some, but by no means all, of the inclusions there is also a solid body contained in the fluid; in some cases this is a transparent cube, in others, and more commonly, an irregular grain or a rod of the solid material. This also has occasionally been observed and described in granites from other districts.

In Metamorphic Limestones.—The metamorphism of the limestone to garnet, epidote, diopside, quartz and other minerals took place under conditions of high temperature and pressure, and almost certainly in the presence of aqueous solutions in fluid or gaseous form. It is a curious fact that these minerals only very exceptionally contain fluid-inclusions. The quartz-grains formed seem entirely homogeneous and free from these interpositions. Only one or two very small inclusions with moving bubble were noted. The same applies to the garnet and other heavy minerals. The calcite would hardly be expected to preserve any such inclusions on account of its perfect cleavage.

In Porphyry.—The inclusions in the porphyry are again practically confined to the quartz. They occur chiefly in the phenocrysts, but also in the quartz of the ground-mass, although they are here usually very small. Naturally, the diorite-porphyries

are poor in inclusions, but they appear abundantly in the granite-porphyries and the quartz-monzonite porphyries with which the ore-deposits are chiefly connected. They are found throughout the Metcalf granite-porphyry, which is characterized by large bi-pyramidal quartz-phenocrysts, and they are almost equally common in the smaller quartz-crystals of the Copper mountain porphyry of Morenci. The sericitization of the porphyry affects them but little, for the quartz-grains of the porphyries are very rarely altered by this process. In specimens taken from the oxidized zone near the surface, many of the inclusions are empty, probably due to the cracking of the grains, and the attending expulsion of the highly-compressed fluid.

The peculiar feature of these fluid-inclusions is that, as a rule, they contain, besides the gas-bubble, an extremely sharply-defined cube of transparent material, and a smaller opaque particle. The invariable recurrence of this association is a proof that these bodies are not accidental inclusions, but were present, dissolved in the fluid, at the time the quartz crystallized and imprisoned the drop of solution.

The inclusions are elliptical, irregularly rounded, or show the form of their host, that is, a hexagonal pyramid with short prism. Their size ranges from those barely visible up to 0.02 mm. in diameter; the latter being about the maximum. A frequently recurring size is 0.012 mm. Their distribution in the phenocrysts is irregular; they are not ranged along any given plane or surface. Moving bubbles are often noted in the smaller inclusions. Heating to 40° and up to 80° C. does not noticeably affect the relation of fluid cube and gas; they do not therefore consist of carbon dioxide, but of some aqueous solution. The proportion of volume between bubble and inclusion is not constant; many of them contain large gas-bubbles, while in others they may be quite small. To some extent this may be explained by leaking, but comparing a great number in very fresh rocks there certainly appears to be considerable variation in this proportion. The fluid is colorless.

As to the cube of transparent salt, it is very sharply defined and well developed. In polarized light the cube appears isotropic. Its size varies, but is usually of about the same volume as the bubble, and occupies from 4 to 15 per cent. of the volume of the inclusion. Such cubes have been sometimes ob-

served before, especially in inclusions contained in quartz crystals; and in some cases they have been proved to consist of sodium chloride. They have also been noted in quartz phenocrysts of certain Cornish granite-porphyries. In the present case the small size of the inclusions, and especially the degree of alteration and oxidation to which most of the specimens have been subjected, renders experimental determination of the salt impracticable, at least with the material in hand at present. It may be said, however, that in all probability the substance is sodium chloride. Several inclusions were measured to determine the degree of saturation when the substance was dissolved in the fluid, assuming that it is NaCl, and that the liquid is a saturated solution of the same salt at ordinary temperature. Results indicate that this was ordinarily from 5 to 20 per cent. above the maximum amount soluble in water under ordinary conditions. In one case it was found that the water must have contained 45 per cent. of salt. Most of the inclusions also contain a small opaque particle, generally measuring only a fraction of the volume of the bubble or the cube. It has no distinct form; occasionally, rod-shaped outlines may be observed, but ordinarily it is so small that it only appears as a black speck. Examined in reflected light, one unusually large particle seemed decidedly black, while another inclusion, contained also in a Copper Mountain porphyry, seemed distinctly reddish in transmitted light.

These inclusions are certainly a characteristic feature of the granite-porphyries of Morenci and Metcalf. They prove, I think, conclusively, that the acid porphyry-magma was accompanied by notable quantities of aqueous solutions containing a large quantity of a salt, which probably was NaCl; and also a smaller amount of some compound containing one or several of the heavy metals. From what follows, it is extremely probable that this compound is largely ferric oxide. It may well also contain copper, although a direct evidence of this cannot be furnished.

These observations gain in interest when it is considered that the porphyry has caused a strong metamorphism of adjoining limestone, the principal feature of which is an acquisition of silica and iron, which in all probability were given off by the porphyry. It is now shown that the magma contained heavy

metals in aqueous solution. Very likely these solutions also contained much silica, but it should be remembered that this material would most likely have been deposited, upon the cooling of the rock, on the walls of the inclusion, and in such a case it would naturally have the crystallographic orientation of the host from which the new substance could not readily be distinguished.

It is perhaps a significant fact that these inclusions are absent in the diorite-porphyries, which, as a rule, have no connection with the copper-deposits.

As to the quantitative importance of the inclusions, it may be estimated that in some specimens they make up a very perceptible percentage of the rock volume.

In Vein-Quartz.—The results of the examinations of the porphyries encouraged a search in the vein-quartz. In a greatly altered pyritic porphyry from the Butler and London tunnel at Morenci, the ground-mass is silicified and contains irregular replacement-veinlets of quartz, which were found to contain inclusions entirely similar to those in the porphyritic quartz with cubic and opaque body. In some cases three small opaque masses were found in one inclusion.

At Metcalf the granite close to the porphyry is greatly shattered and cemented by veinlets of quartz with scattered and minute foils of specularite and occasionally some pyrite. The quartz of the granite has the usual fluid-inclusions mentioned above. The cementing-veinlets of granular quartz are full of remarkably beautiful and fairly large (up to 0.02 mm.) inclusions of the usual rounded or pyramidal-prismatic form. Most of these contain bubble, cube and opaque body. The bubble varies as usual in its relative size; the cube is sharply defined and of the size described under the inclusions in porphyry. In a few of the inclusions the dark bodies are unusually large and have a rounded flat form; they are here translucent with reddish color, and there can be little hesitation in identifying them as ferric oxide or specularite. In some inclusions small grains or crystals, beside the cube, and occasionally transparent matter adhering to the wall, are also found. All this shows that the same or very similar solutions, which formed a part of the magma, deposited quartz in the immediately surrounding rock or in the solidified porphyry itself. It is clear that these solu-

tions must have been very hot and probably also under great pressure, since they held dissolved not only much larger quantities of salt than can be taken up by water at ordinary temperature, but also a substance, which probably is ferric oxide, entirely insoluble under ordinary conditions. This directly connects the solutions contained in the magma with those which deposited quartz shortly after the intrusion and shows that the general quartz-cementation which occurred, closely following the consolidation of the magma, is probably not due to atmospheric waters, but to eruptive after-effects.

In the next place, the strong pyritic, primary fissure-veins were examined, which cut across both porphyry and metamorphosed limestone at Morenci. They are associated with a little normal, coarsely crystalline, vein-quartz. Specimens from the Montezuma vein from different places showed typical vein-quartz full of fluid-inclusions, either irregularly arranged or in places following certain planes in the grains. The quartz-grains often show crystallographic outlines, are occasionally speared by smaller quartz-prisms and are associated with a few large irregular grains of pyrite. Though some of the inclusions are irregular, the majority have rounded outlines, more seldom bi-pyramidal. The size ranges up to 0.012 mm. The relation of bubble and cavity is not constant; many inclusions are empty, no doubt due to leaking, for the quartz is considerably crushed. No change is apparent upon heating the slide to 40° and even to 80° C. Almost always the inclusion contains solid bodies. Cubes, so abundant in the porphyries, are of rare occurrence and seldom well-developed. Most frequent are transparent adhesions to the wall, rod-like masses, pyramidal crystals, or irregular grains. None seem to act on polarized light, possibly on account of the minute size. In most cases the inclusions also contain one or two minute opaque bodies, which cannot be further determined. In a few inclusions the solid material is so abundant as to cause the bubble to assume an elongated form.

Entirely similar inclusions are found in the quartz of the Humboldt vein, occurring as branching-veinlets in porphyry.

The granite along Chase creek, half a mile above the foot of the Longfellow incline, contains many quartz-veins with pyrite, chalcocite and molybdenite. The quartz contains fluid-inclu-

sions, though many of the cavities are empty. Most of the inclusions contain some solid material; a few of these are imperfect cubes; most common are transparent adhesions to the walls, while many also contain opaque bodies.

These observations indicate that the quartz in the fissure-veins was formed in the presence of aqueous solutions of probably several salts. The cubes, so prominent in the porphyry and in some probably earlier veinlets of quartz, seem to be less uniformly present in those of the regular veins. It also follows that the solutions were very hot, for they contained a much larger proportion of salts than can be dissolved at ordinary temperature or even at + 100° C. The opaque bodies indicate that some combination of the heavy metals was also present in the waters.

The quartz-veinlets, connected with the processes of formation of chalcocite and of copper carbonates, contain only few and small inclusions, in which, thus far, nothing but the fluid and the bubble have been observed.

Summary of Genesis.

It has been shown that the intrusions of stocks and dikes of granite-porphyry and quartz-monzonite porphyry, which took place in late Cretaceous, or early Tertiary times, produced an important contact-metamorphism in shales and limestones of Paleozoic age, which happened to adjoin them. This metamorphism resulted in metasomatic development of garnet, epidote, diopside, and other silicates, accompanied by pyrite, magnetite, chalcopyrite, and zinc-blende. The sulphides are not later introductions, but contemporaneous with the other contact minerals.

The contact-zone received very substantial additions of iron oxides, silica, sulphur, copper, and zinc, enough to form good-sized deposits of pure magnetite and low-grade deposits of chalcopyrite and zinc-blende, all of which are entirely unknown in the sedimentary series away from the porphyry.

In view of the evidence, I consider it impossible that circulating atmospheric waters have effected these changes. The occurrences of metamorphosed rocks are manifold and found under many varying conditions; there is only one common factor and that is the presence of the porphyry. It is shown that

the porphyry magma contained much water which held dissolved various salts, among them some of the heavy metals. Sodic chloride and ferric oxide probably predominated. I believe that it contained all of the substances mentioned above, and that large quantities of this gaseous solution (for the critical temperature must have been exceeded) dissolved in the magma were suddenly released by diminution of pressure as the magma reached higher levels, and forced through the adjoining sedimentary beds; the purest and most granular limestones suffering the most far-reaching alteration and receiving the greatest additions of substance. It is thus held that a direct transfer of material from cooling magma to adjacent sediments took place. The formation of garnet indicates large gains of ferric oxide and silica. If the magmatic waters carried iron only as ferric oxide some of it must have been reduced to magnetite during the metamorphism, for the latter mineral is much more common than the specularite. These contact-metamorphic deposits often occur at the immediate contact of the main porphyry stock and the limestones. But more commonly they seem to be connected with dikes of the same porphyry close to the principal mass, these dikes being probably more highly charged with magmatic waters.

It is shown that fissures and extensive shattering developed both in porphyry and altered sediments after the congealing of the magma, and that these fissures and seams were cemented by quartz, pyrite, chalcopyrite, and zinc-blende; forming normal veins largely of the type of replacement-veins. The amount of copper contained in these is usually small, though in places possibly large enough to form pay-ore. The bulk of the veins consists of pyrite. Two classes of veins may be distinguished. The usual type is practically always connected with granite-porphyry or quartz-monzonite porphyry; it occurs in this rock or along dikes of the same. The smaller division consists of those connected in their occurrence with diabase dikes. The genesis of the former type will first be discussed.

As far as the metallic minerals are concerned there is a striking similarity between the veins connected with porphyry and the contact-metamorphic deposits, the only difference being in the magnetite, which does not occur in the veins proper and only subordinately in certain of the altered wall-rocks. A rela-

tionship is also clearly seen in the remarkable action of the vein-solutions on the adjoining wall-rock wherever this is limestone, tremolite and diopside being formed in it by replacement. On the whole, iron and silica are the main substances added, during contact-metamorphism, as well as during the vein-formation.

A study of the fluid-inclusions in the vein-quartz proves conclusively that the veins were formed by aqueous solutions and that these solutions were at a high temperature, for they contained various salts, in part, those of heavy metals, probably iron, which have separated out during the cooling of the crystallized quartz. This entirely eliminates the possibility of deposition by cold surface-waters and points to two or three eventualities. Deposition by atmospheric waters heated by contact with the cooling porphyry, or deposition by ascending magmatic waters, or, finally, by a mixture of both. In any case the metals must be derived from the porphyry, or from deep-seated sources below the porphyry, for, as stated above, the presence of porphyry is the only common factor in all occurrences. It is clear that a positive solution of these problems must be most difficult, but, here again, the fluid-inclusions offer the only direct evidence. In the quartz-seams penetrating the granite near the porphyry-contact at Metcalf, inclusions were found which are indistinguishable from those characteristic of the quartz-phenocrysts in the porphyry, and it must be concluded that the same highly heated and highly charged solutions were active in both cases. This directly connects some of the probably earlier quartz-veins with magmatic water and is evidence of considerable importance. The vein-quartz of Morenci contains inclusions which, in some cases, are identical with those in the porphyry, and in other cases slightly different from them, but always indicate highly heated solutions. The metasomatic action of the waters proves them to have been rich in silica and various salts, among them some of the heavy metals, but entirely deficient in carbon dioxide. Considering this evidence, together with the similarity of the products of these processes with those of contact-metamorphism, I think it certain that parts of the mineral solutions were directly derived from and formed part of the porphyry magma, and I believe it is probable that they were entirely derived from this source.

It seems likely, that the fissuring, which took place after the cooling, opened vents of escape for magmatic waters under heavy pressure at lower levels, and that they ascended on these fissures depositing the heavy metals and the silica and acquiring at the same time carbon dioxide from the sediments which they traversed.

As to the depth at which deposition took place, no positive evidence is available on account of lack of data concerning the extent of erosion. But from stratigraphic consideration, it is not likely that the depth from surface was more than two or three thousand feet. The cause of the deposition was no doubt a decrease in temperature, just as the deposits are formed in the cooled fluid-inclusions. I think it likely that, in most cases, the solutions were present as liquids, for, assuming that the waters communicated with the surface, neither pressure nor temperature could have been high enough to reach the critical point. Probably this does not matter very much, for the properties of water appear to be very similar for some distance each side of this point. Copper, iron and zinc are practically the only important metals present in the main deposits close to the main porphyry stock; but it is interesting and suggestive to note that gold begins to appear in veins which are located some distance away from the central porphyry.

The veins connected with diabase dikes are few in number, and the opportunity for their study has been limited. It seems risky, therefore, to express a definite opinion on their genesis, except that the copper and iron sulphides in all probability were derived from the diabase itself, either by means of magmatic or heated atmospheric waters.

The deposits thus far described are, in general, of low-grade, only rarely containing enough copper to be classed as economically important. Those in shale or limestone consist of disseminated sulphides, in places irregularly concentrated, or accumulated along certain strata, according to the well-defined tendency of contact-metamorphism. Those in porphyry consist of heavy veins of pyrite and a small amount of other sulphides, surrounded by zones of dissemination of the same sulphides.

It remained for the surface-waters, as erosion gradually exposed the deposits, to alter and enrich them in manifold forms.

From the evidence presented above, it must be concluded

that some of the deposits, especially the fissure-veins, were laid bare by erosion, and attacked by surface-waters at an early date, probably before the principal faulting-movement, and certainly before the eruption of the Tertiary basalts and rhyolites. Oxidation has thus acted on them for a very long period.

The irregular and tabular deposits of oxidized ore in limestone and shale have been formed, partly by direct oxidation of sulphides and partly by the influence of sulphate solutions derived from widely disseminated chalcopyrite due to contact-metamorphism; a great enrichment has taken place, due to decrease of volume and addition of copper from the circulating sulphate solutions. Some of the oxidized deposits in shale, however, may be wholly due to adsorption, exerted by the kaolin in the shale on these sulphate solutions.

In the veins, and especially in those which traverse the porphyry stock, or follow porphyry dikes, the history is more complicated. It has been shown that oxidation dates back to Tertiary times, and that the water-level then was considerably higher than it is at the present time. By action of descending sulphate solutions on pyrite, chalcocite was deposited very extensively, and very likely the great vertical extent of the chalcocite-zone, ordinarily from 200 to 500 ft., is due to slow and gradual changes in the water-level. Disintegration and erosion removed the iron-cap (the products of direct oxidation of the primary vein) and began to oxidize the exposed chalcocite-zone. In practically all of the veins, the surface-zone of poor ore is due to the direct oxidation of chalcocite. The solutions from this part descend and add richness to the upper part of the remaining chalcocite-zone. But at the present low stand of the water-level, and the exceedingly dry climate, the lower limit of the chalcocite-zone is probably almost stationary.

The copper-deposits of Clifton and Morenci are thus believed to have been formed primarily by mineral-laden magmatic waters, partly acting as gas and partly as liquids, and in both cases derived from a magma of granite-porphyry. These solutions were evidently directly released from the magma without a preliminary concentration in pegmatitic or aplitic dikes, which, indeed, do not occur in this district in association with the porphyry. It is perhaps superfluous to emphasize

that these conclusions are not generalizations, and that this mode of origin is not necessarily that of all other metalliferous veins.

The earlier processes of magmatic origin produced low-grade deposits of pyritic ores, and the final concentration to payable ore-bodies has chiefly been effected by descending and oxidizing surface-waters of atmospheric origin.

Genetic Classification.

The following scheme of genetic classification of the deposits is presented:

I. First Epoch. Formed during the consolidation of porphyry by laterally moving water-gas.
   a. *Contact metamorphic deposits.*—Irregular or tabular disseminations in shale or limestone, sometimes following stratification planes or dike contacts. Ores consist of pyrite, chalcopyrite, zinc-blende and magnetite. Generally unpayable.

II. Second Epoch. Formed shortly after the consolidation of the porphyry by ascending hot, magmatic waters. Continued on porphyry, granite or more or less altered sedimentary rocks.
   a. *Fissure-veins.*—Lode-systems or single veins. Central seams of pyrite, chalcopyrite and zinc-blende accompanied by wide zones of sericitization and pyritization of the porphyry. Generally unpayable.
   b. *Stock-werks and irregular disseminations.*—Same character of mineralization. Unpayable.

III. Third Epoch. Fissure-veins formed by ascending-waters shortly after the intrusion of diabase.

IV. Fourth Epoch. Deposits formed by descending atmospheric waters acting on Classes I., II. and III.
   a. *Concentrations by direct oxidation and secondary chalcocite-deposition in type I.* Payable.
   b. *Concentrations by direct oxidation and secondary chalcocite-deposition in type IIa.* Payable.
   c. *Concentrations by direct oxidation and secondary chalcocite-deposition in type IIb.* Payable.
   d. *Deposits caused by sulphate-waters along otherwise barren fault-planes.* Occasionally payable.
   e. *Deposits caused by sulphate-waters along shale beds.* Partly payable.

No. 20.

The Copper-Deposits at San Jose, Tamaulipas, Mexico.

BY J. F. KEMP, NEW YORK, N. Y.

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CONTENTS.

	PAGE
I. Introduction,	557
1. Situation,	557
2. Geology,	559
II. Eruptive Rocks,	561
1. Deep-Seated Eruptives,	562
(a) Nephelite-Syenite,	562
(b) Gabbro,	563
2. Laccolith,	563
3. Dikes,	565
(a) Tinguaite,	565
(b) Camptonite,	566
(c) Vogesite,	567
(d) Olivine-Basalt,	567
4. Surface-Flow,	567
(a) Basalt,	567
III. Contact-Effects,	567
IV. Genetic Conclusions,	574
1. Recrystallization Process,	575
2. Absorption Process,	579
3. Process by Contributions from the Eruptive,	579
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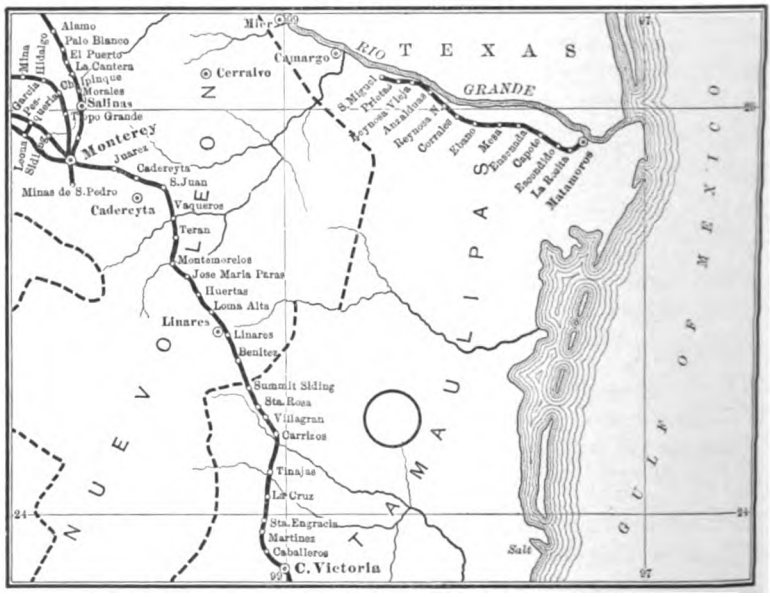

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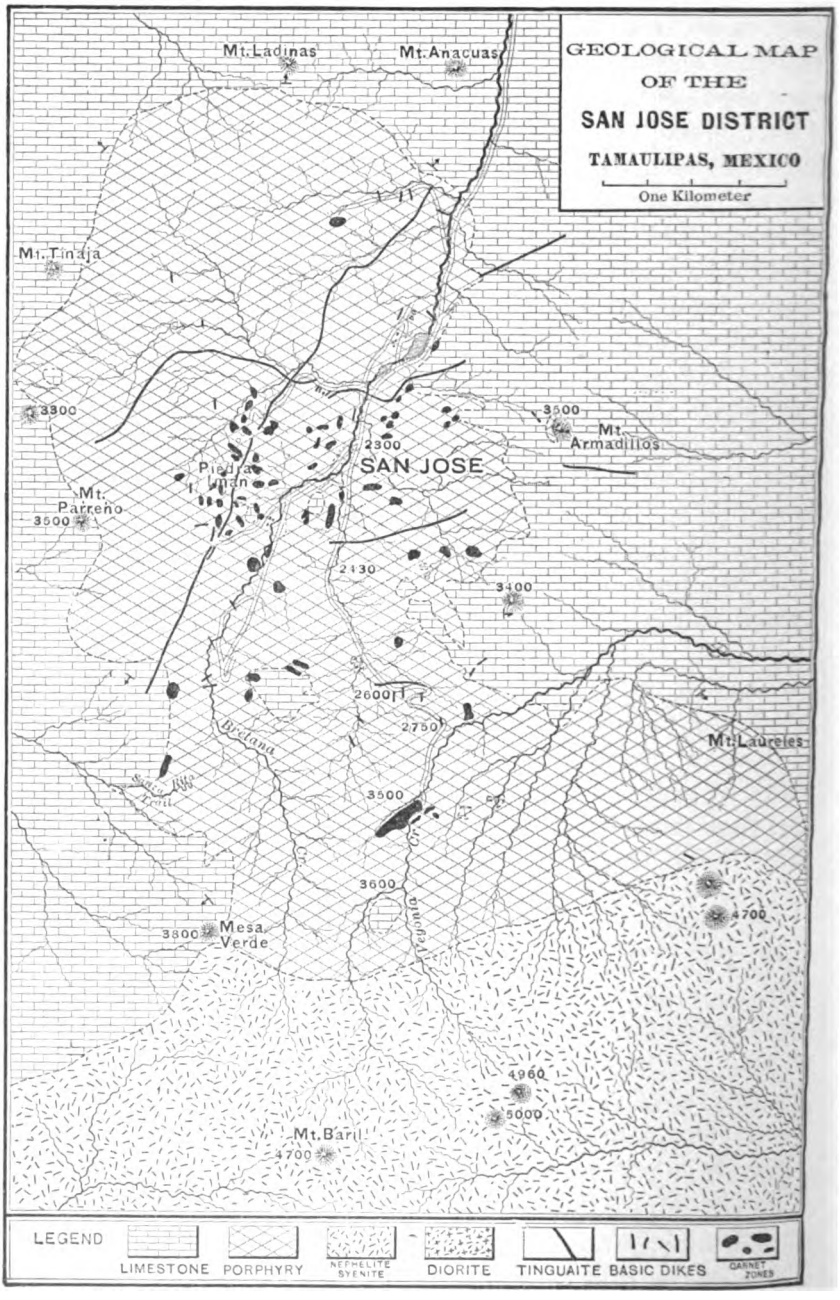

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II. Eruptive Rocks.

The eruptive rocks are of exceptional scientific interest because of the rare types represented. They will be briefly described in their order of age from the oldest to the latest, so far as the succession can be made out. The following varieties are present: Irregular masses of nephelite-syenite and gabbro; the laccolith of diorite-porphyry; about 50 dikes in all of tinguaite, diabase, camptonite, and vogesite; finally a surface-flow of basalt. While some of these names are not generally familiar, a few explanatory sentences under each, as taken up below, will serve to tie them up to varieties which have long been well established.

[1] R. T. Hill. The Cretaceous Formations of Mexico, etc., *American Journal of Science*, Third Series, vol. xlv., No. 268, p. 309 (April, 1893).

1. *Deep-Seated Eruptives.*

(a) *Nephelite-Syenite.*—The oldest of the eruptives is the nephelite-syenite which constitutes the high peaks to the south. It is a rather coarsely crystalline rock, which for all practical purposes may be likened to a granite. It is a peculiar variety of syenite in that it contains the mineral nephelite. The rock is sometimes nearly pure feldspar and nephelite, and is light in color. Again, it has, with these two, more and more black hornblende and pyroxene, until it becomes dark gray. Almost always honey-yellow titanites are visible to the eye. The several varieties have been fully described by Dr. Finlay.

The following chemical analysis, made by Dr. Henry S. Washington, illustrates the composition of one of the varieties: SiO_2, 58.40; Al_2O_3, 20.25; Fe_2O_3, 1.78; FeO, 2.41; MgO, 0.49; CaO, 3.11; Na_2O, 7.01; K_2O, 5.39; H_2O (110°), 0.27; H_2O (ign.), 0.57; TiO_2, 0.25; P_2O_5, 0.20; SO_3, 0.06; Cl_2, 0.2; total, 100.21 per cent. This shows a typical nephelite-syenite rich in feldspar. Dr. Finlay estimated the percentage-composition of the several minerals by measuring areas in thin sections, and, for three varieties of the rock, his results, showing the increasing amounts of the dark silicates, are as follows:

	Percentage of Areas.	Percentage of Areas.	Percentage of Areas.
Orthoclase	60.0	12.0	5.6
Plagioclase	5.0		
Nephelite	25.0	18.0	13.2
Augite	1.0	23.0	13.9
Hornblende	.....	40.0	60.5
Biotite	.....	.....	2.2
Magnetite	8.0	2.7	0.4
Titanite	0.7	2.0	2.8
Apatite	.....	1.2	1.4
Total	99.7	98.9	100.0
Average size of grain	0.36 mm.	0.2 mm.	0.16 mm.

The coarsely crystalline texture of the syenite proves it to be a rock which has consolidated far below the surface, slowly and under pressure. Its present elevated position is believed to be due to faulting, as earlier stated. It is older than the porphyry, but whether it is older than the limestones was not determined, because in no place could the two be found in con-

tact. Whether, therefore, the syenite formed an old land-area and shore along which the limestones were laid down on the sea-bottom, or whether it was intruded into them and later faulted into its present position, we do not know. It is possible, however, that the question could be solved at the western end of the range.

(b) *Gabbro.*—This rock was found in three places, two near each other and mapped as one along the road from San Jose to the Vegonia mine, and one in a gulch northwest of the village. Recent work has shown the former to be somewhat more extensive than is given on the map. The exposures are deeply weathered and rusty brown. The fresh specimens are granitoid in texture, medium grained and dark gray. The constituent minerals are plagioclase, biotite, augite, titanite, magnetite, apatite, pyrite, and zircon. This rock was called a diorite by Dr. Finlay on account of its moderately acidic feldspar, but in order to be clear to readers more especially familiar with rock-names employed in mining-districts, and on account of the preponderating augite, it is here called gabbro. The analyses of slightly differing varieties, made by Dr. Finlay, are: SiO_2, 45.75 (48.49); Al_2O_3, 18.51 (18.99); Fe_2O_3, 6.55 (9.59); FeO, 6.02 (1.00); MgO, 5.06 (5.05); CaO, 11.85 (10.78); Na_2O, 3.41 (3.47); K_2O, 2.35 (1.42); Na_2O, trace (nil); H_2O (100°), 0.06 (0.10); H_2O (ign.), 0.20 (0.55); total, 99.76 (99.44) per cent.

These analyses show the rock to be a rather basic variety, but one which does not differ in any extraordinary degree from those of many gabbros. The syenite and gabbro are two characteristically deep-seated rocks.

2. *The Laccolith.*

The next in order of formation is the rock constituting the laccolith, which is here described under the general name diorite-porphyry. This eruptive combines the features of a deep-seated rock with those of a dike or sheet. It is visibly porphyritic, but the ground-mass, as often happens in laccolithic types, is subordinate and it may almost, if not quite, disappear. The rock therefore shades texturally into a very feldspathic diorite, and in the diamond-drill cores and some of the deeper exposures it can with difficulty be separated, by the eye alone, from the whiter varieties of syenite. The rock is named

the porphyry magma contained much water which held dissolved various salts, among them some of the heavy metals. Sodic chloride and ferric oxide probably predominated. I believe that it contained all of the substances mentioned above, and that large quantities of this gaseous solution (for the critical temperature must have been exceeded) dissolved in the magma were suddenly released by diminution of pressure as the magma reached higher levels, and forced through the adjoining sedimentary beds; the purest and most granular limestones suffering the most far-reaching alteration and receiving the greatest additions of substance. It is thus held that a direct transfer of material from cooling magma to adjacent sediments took place. The formation of garnet indicates large gains of ferric oxide and silica. If the magmatic waters carried iron only as ferric oxide some of it must have been reduced to magnetite during the metamorphism, for the latter mineral is much more common than the specularite. These contact-metamorphic deposits often occur at the immediate contact of the main porphyry stock and the limestones. But more commonly they seem to be connected with dikes of the same porphyry close to the principal mass, these dikes being probably more highly charged with magmatic waters.

It is shown that fissures and extensive shattering developed both in porphyry and altered sediments after the congealing of the magma, and that these fissures and seams were cemented by quartz, pyrite, chalcopyrite, and zinc-blende; forming normal veins largely of the type of replacement-veins. The amount of copper contained in these is usually small, though in places possibly large enough to form pay-ore. The bulk of the veins consists of pyrite. Two classes of veins may be distinguished. The usual type is practically always connected with granite-porphyry or quartz-monzonite porphyry; it occurs in this rock or along dikes of the same. The smaller division consists of those connected in their occurrence with diabase dikes. The genesis of the former type will first be discussed.

As far as the metallic minerals are concerned there is a striking similarity between the veins connected with porphyry and the contact-metamorphic deposits, the only difference being in the magnetite, which does not occur in the veins proper and only subordinately in certain of the altered wall-rocks. A rela-

tionship is also clearly seen in the remarkable action of the vein-solutions on the adjoining wall-rock wherever this is limestone, tremolite and diopside being formed in it by replacement. On the whole, iron and silica are the main substances added, during contact-metamorphism, as well as during the vein-formation.

A study of the fluid-inclusions in the vein-quartz proves conclusively that the veins were formed by aqueous solutions and that these solutions were at a high temperature, for they contained various salts, in part, those of heavy metals, probably iron, which have separated out during the cooling of the crystallized quartz. This entirely eliminates the possibility of deposition by cold surface-waters and points to two or three eventualities. Deposition by atmospheric waters heated by contact with the cooling porphyry, or deposition by ascending magmatic waters, or, finally, by a mixture of both. In any case the metals must be derived from the porphyry, or from deep-seated sources below the porphyry, for, as stated above, the presence of porphyry is the only common factor in all occurrences. It is clear that a positive solution of these problems must be most difficult, but, here again, the fluid-inclusions offer the only direct evidence. In the quartz-seams penetrating the granite near the porphyry-contact at Metcalf, inclusions were found which are indistinguishable from those characteristic of the quartz-phenocrysts in the porphyry, and it must be concluded that the same highly heated and highly charged solutions were active in both cases. This directly connects some of the probably earlier quartz-veins with magmatic water and is evidence of considerable importance. The vein-quartz of Morenci contains inclusions which, in some cases, are identical with those in the porphyry, and in other cases slightly different from them, but always indicate highly heated solutions. The metasomatic action of the waters proves them to have been rich in silica and various salts, among them some of the heavy metals, but entirely deficient in carbon dioxide. Considering this evidence, together with the similarity of the products of these processes with those of contact-metamorphism, I think it certain that parts of the mineral solutions were directly derived from and formed part of the porphyry magma, and I believe it is probable that they were entirely derived from this source.

It seems likely, that the fissuring, which took place after the cooling, opened vents of escape for magmatic waters under heavy pressure at lower levels, and that they ascended on these fissures depositing the heavy metals and the silica and acquiring at the same time carbon dioxide from the sediments which they traversed.

As to the depth at which deposition took place, no positive evidence is available on account of lack of data concerning the extent of erosion. But from stratigraphic consideration, it is not likely that the depth from surface was more than two or three thousand feet. The cause of the deposition was no doubt a decrease in temperature, just as the deposits are formed in the cooled fluid-inclusions. I think it likely that, in most cases, the solutions were present as liquids, for, assuming that the waters communicated with the surface, neither pressure nor temperature could have been high enough to reach the critical point. Probably this does not matter very much, for the properties of water appear to be very similar for some distance each side of this point. Copper, iron and zinc are practically the only important metals present in the main deposits close to the main porphyry stock; but it is interesting and suggestive to note that gold begins to appear in veins which are located some distance away from the central porphyry.

The veins connected with diabase dikes are few in number, and the opportunity for their study has been limited. It seems risky, therefore, to express a definite opinion on their genesis, except that the copper and iron sulphides in all probability were derived from the diabase itself, either by means of magmatic or heated atmospheric waters.

The deposits thus far described are, in general, of low-grade, only rarely containing enough copper to be classed as economically important. Those in shale or limestone consist of disseminated sulphides, in places irregularly concentrated, or accumulated along certain strata, according to the well-defined tendency of contact-metamorphism. Those in porphyry consist of heavy veins of pyrite and a small amount of other sulphides, surrounded by zones of dissemination of the same sulphides.

It remained for the surface-waters, as erosion gradually exposed the deposits, to alter and enrich them in manifold forms.

From the evidence presented above, it must be concluded

that some of the deposits, especially the fissure-veins, were laid bare by erosion, and attacked by surface-waters at an early date, probably before the principal faulting-movement, and certainly before the eruption of the Tertiary basalts and rhyolites. Oxidation has thus acted on them for a very long period.

The irregular and tabular deposits of oxidized ore in limestone and shale have been formed, partly by direct oxidation of sulphides and partly by the influence of sulphate solutions derived from widely disseminated chalcopyrite due to contact-metamorphism; a great enrichment has taken place, due to decrease of volume and addition of copper from the circulating sulphate solutions. Some of the oxidized deposits in shale, however, may be wholly due to adsorption, exerted by the kaolin in the shale on these sulphate solutions.

In the veins, and especially in those which traverse the porphyry stock, or follow porphyry dikes, the history is more complicated. It has been shown that oxidation dates back to Tertiary times, and that the water-level then was considerably higher than it is at the present time. By action of descending sulphate solutions on pyrite, chalcocite was deposited very extensively, and very likely the great vertical extent of the chalcocite-zone, ordinarily from 200 to 500 ft., is due to slow and gradual changes in the water-level. Disintegration and erosion removed the iron-cap (the products of direct oxidation of the primary vein) and began to oxidize the exposed chalcocite-zone. In practically all of the veins, the surface-zone of poor ore is due to the direct oxidation of chalcocite. The solutions from this part descend and add richness to the upper part of the remaining chalcocite-zone. But at the present low stand of the water-level, and the exceedingly dry climate, the lower limit of the chalcocite-zone is probably almost stationary.

The copper-deposits of Clifton and Morenci are thus believed to have been formed primarily by mineral-laden magmatic waters, partly acting as gas and partly as liquids, and in both cases derived from a magma of granite-porphyry. These solutions were evidently directly released from the magma without a preliminary concentration in pegmatitic or aplitic dikes, which, indeed, do not occur in this district in association with the porphyry. It is perhaps superfluous to emphasize

that these conclusions are not generalizations, and that this mode of origin is not necessarily that of all other metalliferous veins.

The earlier processes of magmatic origin produced low-grade deposits of pyritic ores, and the final concentration to payable ore-bodies has chiefly been effected by descending and oxidizing surface-waters of atmospheric origin.

Genetic Classification.

The following scheme of genetic classification of the deposits is presented:

I. First Epoch. Formed during the consolidation of porphyry by laterally moving water-gas.
   a. *Contact metamorphic deposits.*—Irregular or tabular disseminations in shale or limestone, sometimes following stratification planes or dike contacts. Ores consist of pyrite, chalcopyrite, zinc-blende and magnetite. Generally unpayable.

II. Second Epoch. Formed shortly after the consolidation of the porphyry by ascending hot, magmatic waters. Continued on porphyry, granite or more or less altered sedimentary rocks.
   a. *Fissure-veins.*—Lode-systems or single veins. Central seams of pyrite, chalcopyrite and zinc-blende accompanied by wide zones of sericitization and pyritization of the porphyry. Generally unpayable.
   b. *Stock-werks and irregular disseminations.*—Same character of mineralization. Unpayable.

III. Third Epoch. Fissure-veins formed by ascending-waters shortly after the intrusion of diabase.

IV. Fourth Epoch. Deposits formed by descending atmospheric waters acting on Classes I., II. and III.
   a. *Concentrations by direct oxidation and secondary chalcocite-deposition in type I.* Payable.
   b. *Concentrations by direct oxidation and secondary chalcocite-deposition in type IIa.* Payable.
   c. *Concentrations by direct oxidation and secondary chalcocite-deposition in type IIb.* Payable.
   d. *Deposits caused by sulphate-waters along otherwise barren fault-planes.* Occasionally payable.
   e. *Deposits caused by sulphate-waters along shale beds.* Partly payable.

No. 20.

The Copper-Deposits at San Jose, Tamaulipas, Mexico.

BY J. F. KEMP, NEW YORK, N. Y.

(Washington Meeting, May, 1905. *Trans.*, xxxvi., 178).

CONTENTS.

	PAGE
I. Introduction,	557
1. Situation,	557
2. Geology,	559
II. Eruptive Rocks,	561
1. Deep-Seated Eruptives,	562
(a) Nephelite-Syenite,	562
(b) Gabbro,	563
2. Laccolith,	563
3. Dikes,	565
(a) Tinguaite,	565
(b) Camptonite,	566
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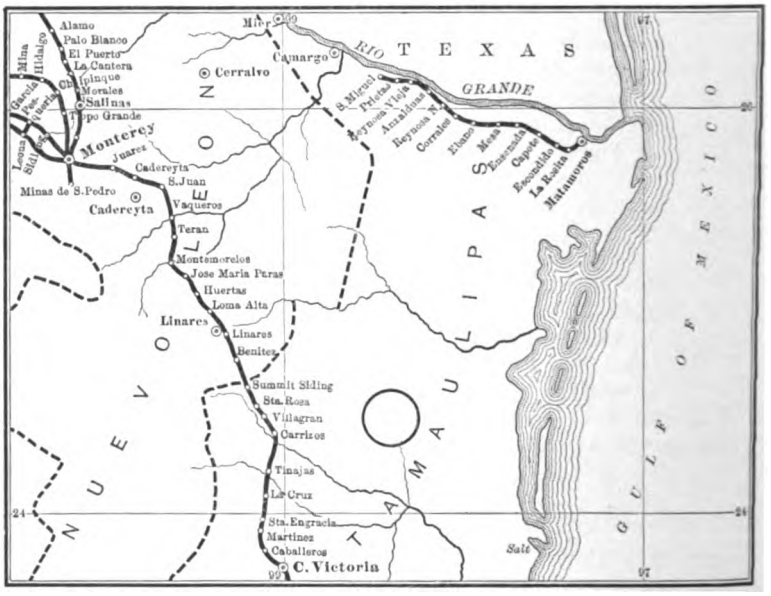

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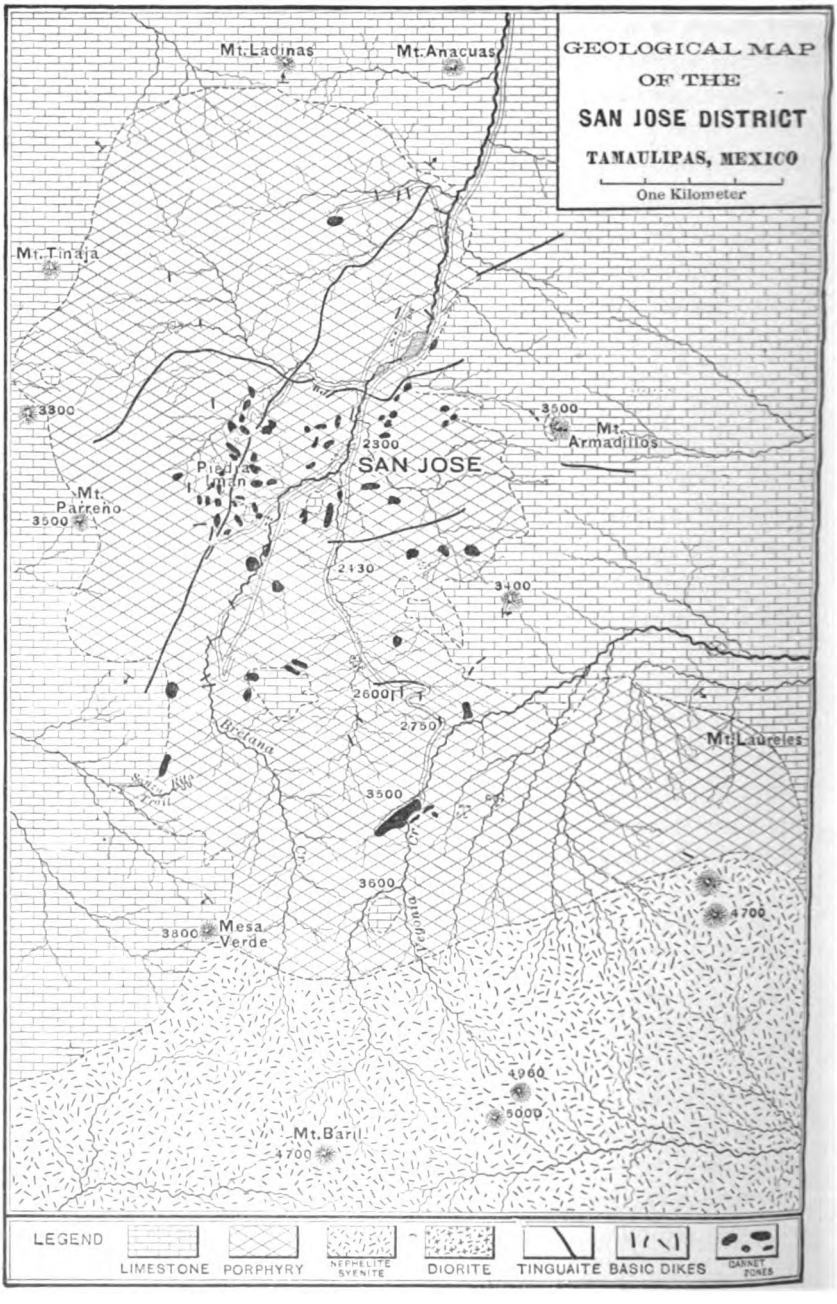

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The limestone is a rather fine-grained bluish variety, where it has not been exposed to contact-metamorphism. It is believed to be Cretaceous and to belong to the very thick formation which is such a prominent feature of northeastern Mexico. It is almost entirely devoid of fossils. I only succeeded in finding one poorly-preserved belemnite and one larger form resembling an *Exogyra*, the latter in a rock altered to a white marble by the neighboring eruptive. R. T. Hill has reported that a formation probably the same with this limestone, but in the valley of the Miquehuana, which is west of Victoria and southwest from San Jose, though still in the State of Tamaulipas, is 20,000 ft. thick.[1] As many earlier observers have remarked, the limestone most closely resembles in its appearance the Palæozoic limestones of the eastern United States and especially the Siluro-Cambrian ones of the Great Valley, which, like the Mexican occurrence, are singularly lacking in fossils. Near San Jose we have neither the top nor the bottom of the series, but there are certainly from 1,000 to 2,000 ft. exposed. The limestone is well bedded and it at times contains streaks of black flint or chert. From the central eruptive area it dips radially outward and is therefore in the form of the great eroded dome, so characteristic of laccolithic intrusions. On the south, however, where the mountains of nephelite-syenite cut off the limestone, this structure does not hold, and it is believed that the nephelite-syenite was elevated by faulting before the intrusion of the laccolith.

II. Eruptive Rocks.

The eruptive rocks are of exceptional scientific interest because of the rare types represented. They will be briefly described in their order of age from the oldest to the latest, so far as the succession can be made out. The following varieties are present: Irregular masses of nephelite-syenite and gabbro; the laccolith of diorite-porphyry; about 50 dikes in all of tinguaite, diabase, camptonite, and vogesite; finally a surface-flow of basalt. While some of these names are not generally familiar, a few explanatory sentences under each, as taken up below, will serve to tie them up to varieties which have long been well established.

[1] R. T. Hill. The Cretaceous Formations of Mexico, etc., *American Journal of Science*, Third Series, vol. xlv., No. 268, p. 309 (April, 1893).

1. *Deep-Seated Eruptives.*

(a) *Nephelite-Syenite.*—The oldest of the eruptives is the nephelite-syenite which constitutes the high peaks to the south. It is a rather coarsely crystalline rock, which for all practical purposes may be likened to a granite. It is a peculiar variety of syenite in that it contains the mineral nephelite. The rock is sometimes nearly pure feldspar and nephelite, and is light in color. Again, it has, with these two, more and more black hornblende and pyroxene, until it becomes dark gray. Almost always honey-yellow titanites are visible to the eye. The several varieties have been fully described by Dr. Finlay.

The following chemical analysis, made by Dr. Henry S. Washington, illustrates the composition of one of the varieties: SiO_2, 58.40; Al_2O_3, 20.25; Fe_2O_3, 1.78; FeO, 2.41; MgO, 0.49; CaO, 3.11; Na_2O, 7.01; K_2O, 5.39; H_2O (110°), 0.27; H_2O (ign.), 0.57; TiO_2, 0.25; P_2O_5, 0.20; SO_3, 0.06; Cl_2, 0.2; total, 100.21 per cent. This shows a typical nephelite-syenite rich in feldspar. Dr. Finlay estimated the percentage-composition of the several minerals by measuring areas in thin sections, and, for three varieties of the rock, his results, showing the increasing amounts of the dark silicates, are as follows:

	Percentage of Areas.	Percentage of Areas.	Percentage of Areas.
Orthoclase	60.0	12.0	5.6
Plagioclase	5.0		
Nephelite	25.0	18.0	13.2
Augite	1.0	23.0	13.9
Hornblende	.....	40.0	60.5
Biotite	.....	.....	2.2
Magnetite	8.0	2.7	0.4
Titanite	0.7	2.0	2.8
Apatite	.....	1.2	1.4
Total	99.7	98.9	100.0
Average size of grain	0.36 mm.	0.2 mm.	0.16 mm.

The coarsely crystalline texture of the syenite proves it to be a rock which has consolidated far below the surface, slowly and under pressure. Its present elevated position is believed to be due to faulting, as earlier stated. It is older than the porphyry, but whether it is older than the limestones was not determined, because in no place could the two be found in con-

tact. Whether, therefore, the syenite formed an old land-area and shore along which the limestones were laid down on the sea-bottom, or whether it was intruded into them and later faulted into its present position, we do not know. It is possible, however, that the question could be solved at the western end of the range.

(b) *Gabbro.*—This rock was found in three places, two near each other and mapped as one along the road from San Jose to the Vegonia mine, and one in a gulch northwest of the village. Recent work has shown the former to be somewhat more extensive than is given on the map. The exposures are deeply weathered and rusty brown. The fresh specimens are granitoid in texture, medium grained and dark gray. The constituent minerals are plagioclase, biotite, augite, titanite, magnetite, apatite, pyrite, and zircon. This rock was called a diorite by Dr. Finlay on account of its moderately acidic feldspar, but in order to be clear to readers more especially familiar with rock-names employed in mining-districts, and on account of the preponderating augite, it is here called gabbro. The analyses of slightly differing varieties, made by Dr. Finlay, are: SiO_2, 45.75 (48.49); Al_2O_3, 18.51 (18.99); Fe_2O_3, 6.55 (9.59); FeO, 6.02 (1.00); MgO, 5.06 (5.05); CaO, 11.85 (10.78); Na_2O, 3.41 (3.47); K_2O, 2.35 (1.42); Na_2O, trace (nil); H_2O (100°), 0.06 (0.10); H_2O (ign.), 0.20 (0.55); total, 99.76 (99.44) per cent.

These analyses show the rock to be a rather basic variety, but one which does not differ in any extraordinary degree from those of many gabbros. The syenite and gabbro are two characteristically deep-seated rocks.

2. *The Laccolith.*

The next in order of formation is the rock constituting the laccolith, which is here described under the general name diorite-porphyry. This eruptive combines the features of a deep-seated rock with those of a dike or sheet. It is visibly porphyritic, but the ground-mass, as often happens in laccolithic types, is subordinate and it may almost, if not quite, disappear. The rock therefore shades texturally into a very feldspathic diorite, and in the diamond-drill cores and some of the deeper exposures it can with difficulty be separated, by the eye alone, from the whiter varieties of syenite. The rock is named

in accordance with the underlying conception that igneous varieties belonging to the andesite-diorite series vary from glassy and felsitic surface-flows of true typical andesites; through porphyritic varieties with increasingly abundant phenocrysts,—the andesite-porphyries of the dikes and sheets,—on through those with less and less ground-mass,—the diorite-porphyries, in laccoliths and stocks,—to the granitoid diorites in the batholiths and deep-seated masses. As the phenocrysts are very abundant and the ground-mass almost disappears in most of the exposures of the laccolith, diorite-porphyry best describes the rock. The name andesite was used by Dr. Finlay, and while I regard with misgivings any change in a nomenclature already, although unavoidably, confusing, the term "diorite-porphyry" is coincident with the usage of Whitman Cross in the folios and papers on the San Juan region of Colorado, where analogous laccoliths occur in many mining-districts. It is hoped that it will therefore be most significant to readers interested in mining-geology.

The diorite-porphyries are light yellow to bluish gray in color and vary by insensible gradations from more basic to more acidic facies. They contain plagioclase, orthoclase, augite, biotite, magnetite, titanite, zircon, and at times quartz in considerable quantity. The ground-mass is fully crystallized and the contrasts are much less between it and the phenocrysts than are usually seen in surface-flows. But this relation always holds in the laccoliths and intruded sheets, as all observers are well aware.

An analysis, made by Dr. Finlay, gave the following results: SiO_2, 62.31; Al_2O_3, 18.63; Fe_2O_3, 2.38; FeO, 1.33; MgO, 0.60; CaO, 5.91; Na_2O, 4.97; K_2O, 3.52; P_2O_5, 0.07; $H_2O(110°)$, 0.16; H_2O (ign.), 0.07; total, 99.98 per cent.

This analysis indicates a rather acidic variety. Column I. of the analyses on the following page gives the percentage-composition of the several minerals obtained by recasting the analysis. Column II. gives the percentage-composition of a still more acidic variety, a dacite-porphry, obtained by measuring the diameters of the minerals in thin sections.

No biotite is tabulated under column I., because, although present in very small quantities, its complicated composition prevents its calculation.

Percentage-Composition of a Dacite-Porphyry.

	I. Per Cent.	II. Per Cent.
Plagioclase	60.0	32.0
Orthoclase	20.6	25.0
Pyroxene	6.6	16.0
Magnetite	3.5	6.7
Quartz	8.9	17.0
Biotite	.....	2.4
Accessories	.....	0.9
Total	99.6	100.0

The diorite-porphyry is the most important rock connected with the ore-formation, since it has produced the garnet-zones and has apparently occasioned the introduction of the ore, as will be later described. Messrs. Aguilera and Ordoñez, who have published a short note about the rock and its contact-zones, speak of it as an andesitic diorite.[3]

Where exposed near the contact-zones, the diorite-porphyry is at times supplied with pyrite which appears throughout the rock and which follows the innumerable tiny fissures ramifying through it in every direction.

The diorite-porphyry is found in the great laccolithic mass and also as innumerable dikes, penetrating the gabbro and especially the limestone, where the latter has been opened up in the mines. It constitutes the greater part of the San Jose valley, its unbroken extent being chiefly prevented by the inclusions of limestone, which resemble islands in the midst of the eruptive mass.

It may be that there is more than one intrusion of the dioritic rock. Considerable range in mineralogy is exhibited; and while no positive field-evidence could be secured, and while the amount of the varieties must be small as compared with the main mass, yet the possibility may be considered.

The diorite-porphyry is later in age than the gabbro, since it cuts the latter in dikes. It is also later than the syenite, since along the contacts it shows the effects of chilling and becomes denser.

3. *Dikes.*

(a) *Tinguaite.*—Dikes of this interesting rock cut the diorite-porphyry in every direction and one in particular runs clear

[3] Bosquejo geológico de Mexico, *Boletin del Instituto geológico de México*, Nos. 4, 5, 6, p. 222 (1897).

across the valley from limestone-wall to limestone-wall. Tinguaites are dense, dark-green rocks closely allied to phonolites, but containing the soda-pyroxene ægirite in great abundance, together with nephelite and orthoclase. A little plagioclase, titanite, magnetite, and in some varieties a great deal of analcite, complete the list of the minerals. Fine phenocrysts of orthoclase are sometimes abundant, but again the rock appears as a dense, green, felsitic one, and then has analcite as a rule.

Two analyses of the analcite-tinguaites, one made by H. S. Washington, the second by G. I. Finlay, are as follows: SiO, 52.83 (49.42); TiO_2, 0.16 (not det.); Al_2O_3, 20.70 (22.99); Fe_2O_3, 2.84 (2.70); FeO, 1.19 (1.89); MgO, 0.41 (0.45); CaO, 1.00 (2.59); Na_2O, 9.94 (9.63); K_2O, 4.97 (4.21); H_2O (110°), 0.37 (not det.); H_2O (ign.), 5.28 (5.73); P_2O_5, 0.03 (not det.); Cl, 0.06 (not det.); total, 99.62 (99.99) per cent.

The tinguaite dikes have been intruded after the formation of the ore and the garnet-zones. They cut the latter and are met in several places in the mines. They also appear as far as 20 miles away from the syenite, both towards San Carlos and towards Linares. Mr. Self concludes that these dikes become more abundant as one leaves San Jose in each of these directions. In other parts of the world tinguaites have proved to be characteristic associates of nephelite-syenites and it is quite natural that they should occur near San Jose. So far as we know, they do not cut the syenite, but are limited to the surrounding rocks.

(b) *Camptonite.*—In great contrast with the green dikes of tinguaite are a number, of dark basaltic habit, which display long, black, slender prisms of hornblende on fresh fractures. They proved on microscopic examination to be the basaltic rock whose chief dark silicate and predominant mineral is chestnut-brown hornblende, and which contains also a little augite, plagioclose, magnetite, and apatite. An analysis by Dr. Finlay yielded: SiO_2, 42.49; Al_2O_3, 17.68; Fe_2O_3, 5.12; FeO, 5.90; MgO, 5.28; CaO, 15.81; Na_2O, 4.29; K_2O, 2.97; H_2O, 0.38; total, 99.92 per cent.

The camptonite is thus a very basic rock. Elsewhere it is a rather characteristic associate of nephelite-syenite and its occurrence at San Jose is quite in accord with the general rule.

The camptonites cut the nephelite-syenite, the diorite-por-

phyry, and the limestone. They are also later than the ore. No intersections have been found which would establish their relative ages as compared with the other dikes.

(c) *Vogesite.*—A 4.5-ft. dike of this interesting rock has been found, which consists chiefly of orthoclase, hornblende, and augite, but there are also small quantities of magnetite, plagioclase, titanite, and biotite. It is practically a very basic syenite, of which hornblende makes up the major part of the rock.

(d) *Olivine-Basalt.*—One other dike of olivine-bearing basalt was found by Dr. Finlay in the syenite area 5 miles south of San Jose. It has, however, no connection with the ores.

4. *Surface-Flow.*

Basalt.—There is also a remarkable surface-flow of basalt which comes out of the eastern side of the San Carlos mountains, in the syenite area, and extends for 4 or 5 miles down the Arroyo Grande. It is scoriaceous and still not greatly reduced by erosion. No cone is associated with it and it seems to be a fissure-eruption. It is the last outbreak in the region. The rock is porphyritic and consists chiefly of plagioclase, augite, and magnetite, with smaller amounts of biotite, titanite, and glass. The habit is basaltic. An analysis by G. I. Finlay yielded: SiO_2, 48.03; Al_2O_3, 20.98; Fe_2O_3, 7.06; FeO, 4.51; MgO, 4.43; CaO, 9.54; Na_2O, 3.28; K_2O, 1.99; H_2O (110°), 0.21; H_2O (ign.), 0.40; total, 100.00 per cent.

This analysis indicates a quite normal olivine-free basalt. The outbreak had nothing to do with the ores and is 5 or 6 miles distant from the nearest mine.

III. Contact-Effects.

The contact-effects are limited to the borders of the diorite-porphyry and the limestone and they are variable in their intensity. The starting-point in their study is the composition of the unchanged limestone, because from this one may infer whether silica and the bases have been added in the metamorphism or whether we are dealing with the rearrangement and crystallization of materials already in the limestone itself. Samples have been very kindly furnished me by E. D. Self, one from an exposure near the Vegonia claim and the other from a quarry operated for flux at the north side of the lacco-

lithic valley and in the surrounding rim. Both were unaltered blue limestone, resembling very much the usual Cambro-Silurian variety so abundant in the Great Valley of the eastern United States. A third sample was taken of a white marble, from the east side of the valley on Armadillos hill. It came from a large mass of limestone, which had been included in the laccolith, and changed to a beautiful, saccharoidal marble.

	Vegonia. Per Cent.	Furnace Quarry. Per Cent.	Marble. Per Cent.
Insoluble	5.04	4.31	9.55
Fe_2O_3, Al_2O_3	0.35	0.95	1.28
$CaCO_3$	94.55	93.83	88.92
$MgCO_3$	0.58	1.29	0.91
Total	100.52	100.38	100.66

These analyses indicate a limestone fairly pure, so far as insoluble silica or silicates go, and one low in magnesia. It may be queried whether the analyses are representative of the general rock of the section, where uninfluenced by the eruptives. Broadly speaking, it seems to me that this is probably not far from the truth. There are some beds with chert observed in the field which would run higher in silica, but these are very minor factors in the total. There may be more argillaceous beds, yet any which are markedly shaly failed to impress themselves upon us, the section presenting a rather strikingly uniform series of limestones. The analysis of marble shows a higher percentage and it is possible that all of it was indigenous in the original unaltered limestone. This sample came from the specimen holding the still recognizable *lamellibranch* fossil, a type of shell favoring muddy bottoms. We may therefore be prepared to admit in some parts of the limestone section even as much as 10 per cent. of insolubles. Still, as the sample showed recrystallization to marble, and as it gave gelatinous silica, and probably therefore contained wollastonite, it may also be true that some silica had been introduced. At this point, however, it is the purpose to state facts rather than draw conclusions, and further discussion is postponed to a later page.

The simplest contact-effect which has been noted is the development of little bundles of tremolite in a limestone which has scarcely lost its blue color. The specimen was found on the southwestern edge of the laccolith near the Santa Rita

trail. For the production of the tremolite it would not seem necessary to assume the introduction of silica from outside, but rather the recrystallization of what was probably already in the limestone, under the influence of heat, or hot waters from the eruptive.

The next effect is to change the blue limestone into white marble. This change is the rule, both with and without the further production of garnet or other minerals. Sometimes the change to marble appears to be the only result brought about by the eruptive. The marble is of the usual variety. It has no associated minerals prominently developed and has been produced by the recrystallization of fairly-pure calcium carbonate with slight admixture of magnesium carbonate. In one interesting case observed on the eastern side of the valley, and already referred to, a fairly well preserved *Exogyra* was still recognizable in the marble.

The most important and extensive contact-effect is the alteration of the limestone to garnet and other lime silicates. Many of the hand-specimens which appear to the eye to be only brown garnet are found to be more complex under the microscope. The production of the lime silicates has taken place on a very large scale. Fig. 2 exhibits 65 different exposures. The focus of change is on the hill called Remedios, the summit of which is the mass of magnetite called the Piedra Iman, or loadstone. The contact-zones are also extensive in Reina hill, and in a general course from the Santo Domingo claim through the Bretana and the San Mauricio towards and to the Vegonia. Around the rim, however, although not absolutely lacking, they are much less common.

The extent of the change varies from scattered nodules of garnet in limestone up to belts and masses many feet across. In most cases they lie along the borders of the limestone and porphyry, but there are occurrences with no visible limestone near, and then the masses of silicates seem to have resulted from the complete alteration of included blocks, torn off by the eruptive.

The garnet and its associated silicates are occasionally in banded or streaked formation, but more commonly they are quite massive. Small vugs or cavities with crystals exhibiting the rhombic dodecahedron are not uncommon. In larger cavi-

ties well-developed octahedral crystals of pyrite also appear, and all through the cavities and along cracks in the garnet, as well as included in its substance, chalcopyrite and pyrite manifest themselves. Some calcite is also occasionally visible in the garnet-zones and, as will be later noted, in two or three places considerable bodies of magnetite have been met, seamed in every direction with chalcopyrite and pyrite. After this general statement the more detailed discussion of the chemistry and mineralogy may be taken up in connection with the individual minerals.

The simplest change in the alteration of the limestone to silicates is the production of wollastonite, CaO,SiO_2 (CaO, 48.3; SiO_2, 51.7), by the replacement of the CO_2 of the limestone with SiO_2. This mineral has only been noted in the microscopic way. It shows an aggregate of brightly-polarizing grains, many of which have a well-marked cleavage with parallel extinctions. In many cases the mineral lacks the elongated, fibrous or prismatic character of the usual wollastonite, but the optical and physical properties indicate its identity.

The next change, which involves the fewest chemical rearrangements, is the production of diopside, the double bisilicate of lime and magnesia, CaO,SiO_2, MgO,SiO_2 (CaO, 25.9; MgO, 18.5; SiO_2, 55.6), which differs chemically from the wollastonite only in the fact that some magnesia is present with the lime. The replacement of CO_2 with SiO_2 is the only change involved. The reaction is the same as in the case of the tremolite, which has essentially the same chemical composition, but the latter was found in the blue limestone, while the diopside has only been observed in the zones of silicates. One slide revealed it in association with garnet and calcite. It formed irregular, brightly-polarizing, almost colorless grains, with its characteristic optical properties. The low percentage of magnesia, both in the limestone and in the eruptive, has militated against its extensive production, garnet, which requires no magnesia, taking natural precedence.

The most widespread and characteristic mineral of the contact-zones from limestone is garnet. Garnet is, however, rather a name for a group than for a single species. The group consists of orthosilicates involving three molecules of H_4SiO_4 and having twelve bonds of affinity which are satisfied by three pro-

toxides, such as CaO and FeO; and by one sesquioxide, such as Al_2O_3 or Fe_2O_3. By combinations of these, several distinct garnets can be made. Thus, $3CaO, Al_2O_3, 3SiO_2$ is grossularite,

Grossularite.

$$\left.\begin{matrix} Al \\ Al \end{matrix}\right\} \begin{matrix} SiO_4 = Ca. \\ SiO_4 = Ca. \\ SiO_4 = Ca. \end{matrix}$$

Andradite.

$$\left.\begin{matrix} Fe \\ Fe \end{matrix}\right\} \begin{matrix} SiO_4 = Ca. \\ SiO_4 = Ca. \\ SiO_4 = Ca. \end{matrix}$$

the one which has been usually considered to be present in the zones. The fact that the garnets are light brown or pale green has given rise to this impression in the absence of chemical analysis, and upon the basis of the grossularite molecule the inferences about the constitution of the original limestone and development of the zones have usually been reached. Some doubt, however, arose in my mind regarding the correctness of this view and a massive variety was selected for analysis. It was a pale reddish brown in color. The results obtained, including the molecular ratios, are as follows:

	Per Cent.	Molecular Ratios.
SiO_2	37.15	619
Al_2O_3	6.98	69
Fe_2O_3	19.40	120
CaO	32.44	576
$CaCO_3$	4.20	
Soluble Al_2O_3, Fe_2O_3	0.43	
Total	100.60	

It was found on trial that the sample contained some calcite. It was therefore treated with very dilute hydrochloric acid and from the solution enough lime was obtained to make 4.20 $CaCO_3$. The solution also yielded 0.43 Al_2O_3, Fe_2O_3, with perhaps a little SiO_2; the total was so small that no attempt to separate the constituents was made. No visible magnesia could be precipitated. It is possible that a little manganese was also present in the sample. It was not specially sought.

If we recast the above analysis so as to determine the relative amounts of the grossularite and andradite molecules, the results are as follows, using respectively the molecular ratios of the alumina and ferric iron as the basis.

Grossularite.			Andradite.		
3CaO	207	11.60	3CaO	360	20.10
Al_2O_3	69	6.98	Fe_2O_3	120	19.40
$3SiO_2$	207	12.42	$3SiO_2$	360	21.60
		31.00			61.10

There are not sufficient molecules of the alumina and ferric iron to care for all the silica and lime. The excess of the former is $619 - (207 + 360) = 52$, corresponding to 3.12 per cent. This would lead one to infer the presence of a little quartz in the sample, or else that in the garnet there was some diopside or wollastonite, both of which contain more silica than does garnet. Yet in any event the amount does not seriously affect the result. The lime is as follows, $576 - (207 + 360) = 9$, corresponding to 0.5 per cent. This may be due to the supposed diopside or wollastonite, as just stated, or perhaps to error in the analysis. It also is not a serious factor. The chief result of importance, even admitting slight errors in determinations and assumptions, is to establish the relative amounts of the grossularite and andradite molecules. These are to each other as 31 to 61.1, or in percentages—grossularite, 33.7; andradite, 66.3.

The lime-iron garnet must therefore be esteemed of very great importance in the chemistry of the production of the zones, and theoretical discussions based on the grossularite molecule are open to objection to this extent. The importance of the whole matter lies in its bearing upon the question of the production of the garnet, whether by recrystallization of an impure limestone or by contributions of silica, alumina, and iron from the eruptive to a fairly-pure limestone. This question will be taken up later. It may be remarked, however, that Waldemar Lindgren [4] also records the presence of the andradite molecule in large amounts in the zones at Morenci, Ariz., although the analyses have not yet been published.

In association with the garnet is also found vesuvianite, a still more complicated compound, regarding whose exact formula there has been some difference of opinion. Writing it as it is given by F. W. Clarke,[5] it is $HCa_5,MgAl_3,Si_5O_{21}$, or if we expand

[4] The Genesis of the Copper-Deposits of Clifton-Morenci, Arizona, *Trans.*, xxxv., 511 to 550 (1904); p. 517, this volume.

[5] *Bulletin No.* 125, *U. S. Geological Survey*, p. 25 (1895).

it into a graphic form, which always helps towards a clear understanding, the following is obtained:

$$H—Al = SiO_4.$$

$$\begin{array}{l} Al \diagup\!\!\!\diagup \\ \quad\quad SiO_4 = Ca. \\ Ca \diagup \\ \quad\quad SiO_4 = Mg. \\ Ca \diagup \\ \quad\quad SiO_4 = Ca. \\ Ca \diagup \\ \quad\quad SiO_4 \equiv Al. \end{array}$$

The vesuvianite, as compared with the other minerals, only involves the addition to the limestone of the same silica, alumina, and ferric oxide, together with hydroxyl or hydrogen; and both of the last named could easily be supplied by steam, conceivably dissociated under the pressures and temperatures attendant on igneous intrusion. The vesuvianite has been observed in one rare instance extending out as a small vein, 1 in. wide by 4 in. long, into the limestone, as if it had been formed on either side of a small crack by the introduction of the elements needed to change over the neighboring limestone. In the general mass of the contact-rock the microscopic examination has not indicated that it is frequent.

Of the other silicates, epidote, zoisite, biotite, albite, anorthite, etc., which are sometimes met in limestone-contacts, no occurrences have been noted.

Magnetite is a contact-mineral locally developed in irregular masses, which are of very considerable size. On the borders there are intermingled garnet and diopside, and throughout the magnetite are abundant veinlets of chalcopyrite and pyrite, but sections of the magnetite exhibit practically no transparent minerals. One prominent outcrop gave the name Piedra Iman, or loadstone, to the summit of Remedios hill. A large mass has been opened in the Santa Elena claim.

The magnetite must have been introduced in the same way as have the silica and alumina which have developed the silicates. The iron oxide has probably replaced the limestone and has thus formed local contact-masses different from the usual type. So far as the available evidence goes, the introduction of the magnetite has followed the garnet and diopside and has

preceded much of the chalcopyrite and pyrite, since all manner of crevices in it are filled with veinlets of the latter.

In small pockety masses throughout the garnet and other silicates calcite is occasionally seen. It may be either residual limestone not changed over into silicates, or it may be calcite of secondary introduction.

Molybdenite has also been found by E. D. Self to be quite abundant in some of the workings opened since my visit. Thus in the Santa Elena adit, assays covering a considerable distance yielded from 0.5 to 1 per cent. of MoS_2. In the Santo Domingo shaft Mr. Self has observed it, apparently in a garnet-zone that contained also vesuvianite. The occurrence of molybdenite at San Jose corresponds with Mr. Lindgren's observations at Morenci. The home of molybdenite is in the pegmatite dikes, and it is interesting and suggestive to find it also in the zones, which must likewise be ascribed to expiring igneous activities.

The most important copper-mineral is chalcopyrite, quite invariably in association with pyrite. The two must have come in together. They appear not only as inclusions in the silicates, but also as veinlets and as coatings in cavities. They cover at times the well-developed crystals of garnet so as to mold around them like a paste. The sulphides may themselves form large masses analogous to the magnetite and thus yield the best stopes of ore.

The usual oxidized compounds malachite, chrysocolla and, less often, cuprite may be seen. The mine-waters from the Santo Domingo shaft yield appreciable amounts of dissolved copper.

Since my visit, narrow veinlets of sulphide ore rich in gold have been discovered in the porphyry and far from known limestone or garnet-zones, as observed by Mr. Self. These occurrences suggest parallels with Morenci.

IV. Genetic Conclusions.

Having the comprehensive statement of the minerals and their relations to the contact-zones before us, we may consider the possible, as well as the most reasonable, methods whereby they could have been produced. As incontrovertible we may establish at the outset the following premises :

1. The garnet-zones have been produced by the action of the diorite-porphyry upon the limestone.

2. The garnet-zones are irrrgular in distribution and in size. They are sometimes very thick, and again white marble is alone developed next the eruptive.

3. The chemical compositions of the active agent, the diorite-porphyry, and of the raw material, the limestone, are as follows. Some, though probably not great, variation is admissible for each. To these are added the theoretical analyses of andradite and of grossularite, the most abundant molecules in the zones.

Diorite-Porphyry.		Limestone.	
	Per Cent.		Per Cent.
SiO_2	62.31	Insol	4 to 5
Al_2O_3	18.63	Al_2O_3, Fe_2O_3	0.5 to 1.2
Fe_2O_3	2.38	$CaCO_3$	93 to 94
FeO	1 33	$MgCO_3$	0.5 to 1.2
MgO	0.60		
CaO	5.91		
Na_2O	4.97		
K_2O	3.52		
P_2O_5	0.07		
H_2O	0.23		
Total	99.95		

Andradite.	
	Per Cent.
SiO_2	40.0
Al_2O_3	22.7
CaO	37.3
Total	100.0

Grossularite.	
	Per Cent.
SiO_2	35.4
Fe_2O_3	31.5
CaO	33.1
Total	100.0

1. *The Recrystallization Process.*

We may first raise the question whether it is conceivable that the garnet has been produced from the limestone alone. That is, are we justified in believing that the limestone was sufficiently siliceous and argillaceous, where we now find the zones, to have yielded the garnet and the other silicates without contributions from the eruptive? The belief that contact-zones are formed in this way is rather widespread and is based partly on general considerations and partly on the following specific cases:[6]

1. In studying the contact-effects produced by the famous Shap granite of Westmoreland, England, upon amygdaloidal and altered basaltic rocks which it crosses, Alfred Harker concluded that the contact-minerals produced from the amygda-

[6] For a general review of views upon this question with citations of authorities, see W. Lindgren, The Genesis of the Copper-Deposits of Clifton-Morenci, Arizona, *Trans.*, xxxv., 519 to 524 (1904); p. 517, this volume.

loidal fillings did not involve new contributions from the granite nor the migration of the old materials farther than $\frac{1}{10}$ inch.[7]

2. Great bodies of favorable eruptive rocks, such as granite, sometimes break across thick sections of sedimentary rocks of all sorts, perhaps miles in extent, and yet produce extremely variable effects. Thus Dr. Joseph Barrell has described a case in the Elkhorn district, Montana. A mass of granitic rock has cut a thick sedimentary series. It has produced but slight changes where it penetrated pure limestones, the new minerals scarcely extending 5 ft. from the contact; whereas, where it cut the Starmount limestone, recognized to be siliceous and argillaceous, it has changed the latter to a mass of lime silicates and feldspars for a quarter of a mile from the eruptive. The average composition of the contact-zone is, grossularite, 60; diopside, 25; wollastonite, 15; total, 100 per cent.

When referred back to an original limestone which would yield this mixture Dr. Barrell[8] found by recasting the mineralogy that it must have contained quartz, 21.3; kaolinite, 25.0; calcite, 46.6; magnesite, 7.1; total, 100 per cent.

The magnesite molecule was of course combined with the calcite in dolomite. If we express the above in percentages of oxides they will be, SiO_2, 32.9; Al_2O_3, 9.9; CaO, 26.1; MgO, 3.38: CO_2, 24.22; H_2O, 3.5; total, 100 per cent.

Dr. Barrell does not give any analyses of the Starmount limestone, but from field-observation he apparently esteemed it to be sufficiently siliceous and aluminous to yield the lime silicates. On the other hand, on p. 291 of the paper in the *American Journal of Science*, it is stated regarding the contact-zones from this limestone that

"The rocks are dense and even-grained and without cracklings or infiltrations of quartz or calcite. The thin sedimentary banding is still preserved with the same lenticular, somewhat concretionary structure observed at a distance from the igneous intrusions, and the adjacent layers, where of different mineral composition, are sharply separated from each other. Certain strata may show a few

[7] *Quarterly Journal of the Geological Society*, vol. xlix., No. 195, pp. 368 to 369 (Aug., 1893).

[8] Physical Effects of Contact-Metamorphism, *American Journal of Science*, Fourth Series, vol. xiii., No. 76, pp. 291 to 292 (Apr., 1902). See also Weed and Barrell, *Twenty-Second Annual Report, U. S. Geological Survey*, Pt. II., p. 399 (1900–01).

per cent. of calcite, but this is distributed in a manner which indicates that it is not a secondary addition, but on the contrary is due to those beds containing originally more calcium carbonate than could combine under metamorphic action with the quartz and kaolin present. These features sharply separate the mass of Starmount strata from certain beds, which owing to special conditions do show infiltrations, as indicated by nuclei of quartz with fluorite and ore grains."

Three paragraphs further on it is stated on p. 292.

"In the process of metamorphism this mass of strata [*i. e.*, the Starmount] has lost approximately 28 per cent. of its weight, and 45 per cent. of its volume, from 70 to 90 times its volume of water vapor and 320 volumes of carbonic dioxide, the gases being measured at 0° C. and 760 mm."

While it is the purpose at this point to state, with all possible emphasis, the points favorable to the recrystallization of the material *in situ*, and while the perfect preservation of the old bedding with the introduction of new material may not be without difficulties, yet one cannot but remark in passing that the production of a rock "dense and even-grained and without cracklings," while at the same time losing "28 per cent. of its weight and 45 per cent. of its volume," is also fraught with other, perhaps greater, difficulties.

3. We sometimes find the zones of silicates, even in the same great stratum of limestone, following certain beds for a long distance away from the eruptive, while the beds on either side are white marble. The zones may even be greatly contorted and yet persistent. Dr. W. L. Austin has called my attention to a very striking illustration of these relations at Sacrificio mountain, Nombre de Dios, Durango, Mexico, of which a photograph is reproduced in Fig. 3, in which the zones are wollastonite. It would seem from this as if the siliceous beds yielded wollastonite, and the neighboring calcareous beds, marble. No doubt these cases strongly favor recrystallization *in situ*. The interesting zones at San Pedro, N. M., described by Messrs. Yung and McCaffery,[9] might also be considered to give additional support when one studies the map and section, showing the occurrence of both shaly and purer limestones, but they also remark (p. 355), "The limestone left in contact with the garnet is always more siliceous than the limestone further removed from the ore-body," and as will be brought out for San Jose, it does not seem probable, when the varying occurrences

[9] The Ore-Deposits of the San Pedro District, N. M., *Trans.*, xxxii., 350 (1901).

of the garnet rock are properly considered, that the eruptive, when the garnets were developed, happened always to be next to a specially siliceous portion.

Before we turn to the considerations positively favoring the contribution of material from the eruptive, it may be remarked that wide experience has demonstrated that the development of contact-effects is, as a rule, irregular, showing great strength at certain places and a well-nigh incomprehensible failure at other, apparently equally favorable, points. We have best accounted

FIG. 3.—ZONES OF WOLLASTONITE IN MARBLE, NOMBRE DE DIOS, DURANGO, MEX.

(From a photograph by W. L. Austin.)

for these relations by believing that the contact-effects are the results of the emission of gases, vapors, and liquids, especially water in its several physical states, and that these were freely afforded at certain points and failed at others. There is great reason for believing that this is true. Those eruptives, moreover, which fail to produce contact-effects, are probably lacking in the dissolved gases, etc., and are cases of relatively dry fusion.[10].

Admitting the addition of material from the eruptive, two possible methods are to be considered. A contact-zone may be

[10] This subject is briefly summarized in Kemp's *Handbook of Rocks*, 3d ed., Chapter IX.

due to the fusion of the wall-rock into the eruptive and its consequent absorption, yielding a product of intermediate composition; or it may be due to the emission of gases, vapors and heated liquids in the process generally described as hydrothermal. We may consider the first method at the outset.

2. *The Absorption Process.*

The garnet-zones at San Jose are in a general way intermediate in composition between the eruptive and the limestones; but, so far as observation goes, they lack feldspar entirely, and this mineral ought not to fail if absorption took place. Moreover, the irregularity of distribution; the sharp contacts; the obvious effects of chill on the eruptive, as shown by the changes in texture and the occasional presence of scattered garnets in predominating limestone, all militate against its application. Experiments, moreover, in the artificial production of garnets of the grossularite type have shown that when their component materials are fused together, or when they themselves are melted, the resulting product is anorthite, melilite, and pyroxene. Therefore, while absorption-phenomena have been with good reason called into play to account for some contact-phenomena, as, for instance, the curious rocks at Pigeon Bay, Minn., described by W. S. Bayley;[11] yet in the typical garnet-zones they have small claims to confidence.

3. *The Process by Contributions from the Eruptive.*

In the cooling of the eruptive there must have been a stage when the emissions were of necessity gaseous, and a later stage when they were liquids, and still a third stage when meteoric waters, if such could penetrate to the still heated eruptive, must have been set in circulation by it at temperatures below the boiling-point, else it is difficult to conceive of water reaching the heated eruptive against steam-pressure, except perhaps very locally and for a brief season.

In his study of the Clifton district, Mr. Lindgren has attributed the garnets and other silicates to the stage of gaseous emissions, particularly of water-gas accompanied by silica and iron. This is quite reasonable, and it may be that at San Jose the garnet-zones, the magnetite, and the copper-ores were formed

[11] *Bulletin No.* 109, *U. S. Geological Survey* (1893).

at this time. From the evidence in hand, however, there seems no reason to eliminate heated waters as also possible agents. The chief and most tangible interest centers around the question of the introduction of silica, iron, and perhaps alumina, from the eruptive.

That these three must have been added to the limestone in order to produce the zones of silicates, the chemical analyses of the unaltered rock and the field-observations make practically certain. Otherwise we cannot easily understand how limestones ranging from 4 to 5 per cent. of insolubles attain to from 40 to 50 per cent. of silica and alumina. Regarding the silica and the iron there is no special chemical difficulty, but the alumina is perhaps different. In the general weathering of rocks, such as granites, we usually consider the alumina as the stable oxide, and, assuming that it remains comparatively unaffected by the natural agents, we calculate back to original compositions. At the same time, we have as a suggestive compound of aluminum the fluoride, cryolite, a mineral easily soluble in sulphuric acid, with the evolution of hydrofluoric acid. Its properties would suggest the inference that at the temperatures and pressures prevailing during the cooling of a rather deep-seated intrusive rock, it may well happen that aluminum is far from being inert. When we compare its great abundance in the porphyry, from 18 to 19 per cent., with the 1 per cent. and less in the limestone analyzed, the former seems to be much the more probable source.

Again, if we are still favorably inclined to believe in an original siliceous and argillaceous composition of the limestone and, recognizing the comparative rarity of this variety so far as observation goes, if we try to conceive of just this variety happening to be next the eruptive wherever we find the garnet-zones, widely distributed as they are, both vertically and horizontally; shading off as they occasionally do into pure white marble, without regard to original stratification; and in neighboring places abruptly failing in favor of the marble,—we are confronted with grave difficulties—much graver ones, in fact, than are presented by the assumption that the eruptive contributed the necessary materials.

Still again, if we recall the fact that the garnet-rock is on the whole a fairly dense and solid variety, which might be pro-

duced from limestone by new contributions of silica, alumina, and iron, able to take the place of the eliminated carbon dioxide; whereas, the recrystallization of an impure limestone requires the production of cavities, theoretically more than 40 per cent. of the original volume; we shall find for the San Jose case that the addition of new material involves fewer difficulties and is, in fact, the only reasonable explanation. The cavities, which are observable and which are filled in part by the sulphides, are probably due to the rearrangements brought about by the combination of the 4 or 5 per cent. of insolubles with the lime of the calcite and the attendant loss of carbonic acid involved.

The bodies of magnetite were doubtless formed by direct replacement of the limestone with the iron oxides and seem to indicate a local richness in iron for the emissions from the eruptive where they are found. There is slight, if any, reason to regard them as other than purely contact-products. One or two little pockets of specularite were observed, but this mineral does not exhibit the abundance shown elsewhere, as, for instance, in the zones at the Seven Devils, Idaho.

The introduction of the sulphides seems to have been in largest part one of the later phases of the contact-metamorphism and to have followed the production of the silicates, at least in part. We infer this from the relations described under the sulphides that, besides forming inclusions in the silicates, they mold around the garnets, and follow crevices in the magnetite. Where they constitute large masses they doubtless replaced the limestone, although in the midst of the contact-zones.

4. *Oxidized Ores.*

The production of the oxidized minerals has been favored in at least one or two cases by faults. It is possible to show the existence of the latter by the heaved condition of the tinguaite dikes, and near the natural conduit thus afforded for the descending meteoric waters the formation of oxidized minerals has been recognizable.

As is often the experience with copper-ores in deposits of this type, a small amount of gold is shown by the assays. Other metals are practically lacking and the matte is very clean.

No. 21.

The Magmatic Origin of Vein-Forming Waters in Southeastern Alaska.*

BY ARTHUR C. SPENCER, WASHINGTON, D. C.

(Washington Meeting, May, 1905. *Trans.*, xxxvi., 364.)

HAVING suggested magmatic waters as the probable agents of vein- and ore-deposition in southeastern Alaska in a paper entitled, The Geology of the Treadwell Ore-Deposits,[1] it is with particular interest that I note W. Lindgren's application of the hypothesis of igneous emanations to the gold-quartz veins of Victoria and of California.[2]

Mr. Lindgren says:

"In the above paragraphs I have repeatedly called attention to remarkable similarities in vein-filling and metasomatic action between the Victorian quartz veins and those of Sierra Nevada. Another striking similarity is that in both of these regions the veins were formed just after the intrusions of vast masses of granite or dioritic magma into crumpled and compressed sediments. I am convinced that these similarities are due to closely similar modes of formation. With some confidence, I would formulate the hypothesis that the gold and the quartz in this type of veins have been deposited chiefly by '*eruptive after-effects*;' in other words, chiefly by hot ascending waters originally contained in the granitic magma and released from it by decreasing pressure, due to its eruption into the upper parts of the lithosphere. It is quite possible that atmospheric waters may have played a certain part by aiding the precipitation and by effecting certain forms of concentration in the deposits."

There are many reasons for extending this hypothesis to southeastern Alaska. This region and the Sierra Nevada belt of California are undoubtedly parts of one geologic province, throughout which the main events of geologic time are evidenced by identical or closely similar records in the rocks. Our knowledge of the former region is still fragmentary, to be sure, but the origin-dates of the most prominent features of

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[1] *Trans.*, xxxv., 473 (1904).

[2] Characteristics of the Gold-Quartz Veins of Victoria, *Engineering and Mining Journal*, vol. lxxix., No. 10, p. 460 (Mar. 9, 1905).

geology have been located in the time-scale, and found to correspond completely with the red-letter dates in the California record. In both regions, viz.: (1) intense folding and metamorphism followed the deposition of strata which palæontologists agree are either uppermost Jurassic or lowest Cretaceous (Mariposa beds of California); (2) intrusion of granitic rocks (mainly granodiorite and diorite) accompanied the later stages of folding or closely followed the plication and metamorphism; (3) after the intruded rocks had solidified both they and the inclosing formations were fractured; (4) the multitude of wounds were healed by the deposition of vein-fillings, the mineralogy of which corresponds in almost every respect in the two fields; and finally, (5) erosion ensued and was followed by the deposition of formations of Tertiary age.

Reasoning from the above outline alone, is it not to be expected that the origin of the veins in the two regions must be identical, and does it not add strength to the suggested hypothesis that it has been developed and applied independently in two regions geologically so similar?

Students of ore-deposition will wait with keen anticipation a complete exposition by Mr. Lindgren of the data on which his hypothesis is based. My own suggestions concerning the veins of southeastern Alaska are necessarily founded on a very incomplete knowledge of the facts involved, since all of the observations upon which they rest were made during a single summer. The hypothesis here presented, therefore, undoubtedly borders too closely on pure speculation to carry much weight by itself. Nevertheless, none of the data at hand seem to be antagonistic to it, and it is hoped that by stimulating the collection of data having a definite bearing *pro* or *con* its prematureness may be in a measure compensated.

The most striking feature of geology in the Alaska Panhandle region is the great dioritic core of the Coast range, a complex of coarsely-granular intrusive rocks which is known to be continuous from near the northern boundary of Washington State to beyond the head of Lynn canal. Outside of this band, many masses of similar rock occur throughout the Alexander archipelago, and likewise in the region back of the coastal barrier in British Columbia.

The wide occurrence of this invading rock has led to the

conception that it may exist as an underlying mass throughout a very extensive region, in which the surface-formations are mainly metamorphosed sedimentary rocks comprising representatives of the different geologic periods from Silurian to Lower Cretaceous.

Metalliferous quartz veins are found in all parts of the region, though in general they occur less frequently in large intrusions than in small masses of diorite, and are most numerous in the metamorphosed formations which inclose the intrusive rocks. They are quite as numerous away from the bodies of diorite as near them and, in fact, show no distribution relation to the masses of intrusive rock. From the structural features of the veins there can be little doubt that most of them were formed during a single period of water-circulation which followed not only the invasion of the diorite, but, in fact, the complete solidification of those parts of the intrusive masses now exposed to view.

Seeking to explain the relations observed and to determine the source of the vein-forming waters, it may be assumed that the deep-seated portion of the magma which furnished the Coast range diorite remained in an unconsolidated condition long after the complete crystallization of the masses observable at the present surface. Under certain conditions the existence of a deep-seated and widely-distributed magma in any region might be favorable to the production of general fracturing in the solid rocks above it, and the magma itself might well be the principal source of the vein-waters. Leaving the origin of the vein-openings for separate consideration, let us turn to the question of the magma as a source of vein-forming solutions.

If, during and subsequent to the fracturing of the rocks, the abyssal portion of the magma was gradually consolidating, it must have given off large amounts of water, for it is now generally agreed by petrologists that the order of crystallization exhibited by the minerals of the granular rocks can be best explained by admitting the existence of more water in the magma before and during its consolidation than is shown by analysis of the resulting rock. Accepting this, crystallization would be the *sine qua non* for a continuous and sufficient supply of water, which can be properly conceived of as containing in solution all the elements necessary to form the observed

veins. Deposition from such magmatic or original waters would be controlled by any or all of such circumstances as decrease of pressure or temperature, metasomatic action on the country-rocks, and mingling with solutions which might bring about chemical reaction.

The applicability of the hypothesis depends upon (1) the existence of the supposed extensive bed of diorite beneath the area in which the veins occur, (2) the possibility that such a mass could rid itself of water freed during the process of crystallization, and (3) the competence of solutions of magmatic origin to produce the results observed.

The first requirement may be assumed to exist in the region under discussion on the ground of probability, while the second and third, which are inherent in all problems of ore-deposition where the instrumentality of magmatic solutions is suspected, can be reasonably inferred from well-known observations. The manner in which water has escaped from masses of rock during deep-seated solidification is not readily arrived at, but, that most magmas must have contained more water than is to be found in their crystallized products, that is to say, in the rocks, is reasonably well established, and is accepted by such recent writers as J. H. Vogt, J. F. Kemp, A. C. Lane, and C. R. Van Hise. The fact that water must have escaped is patent from a comparison of the dryness of the rock with the fairly-presumed wetness of the magma.

As to the ability of magmatic solutions to produce quartz veins carrying gold and metallic sulphides, sometimes, as in Australia, California, and Alaska, with albite and rutile, or with tourmaline, there can be little doubt. During deep-seated solidification, the material dissolved in the magma-water will vary with the progress of fractional crystallization, and as crystallization proceeds the mother liquor, that is to say, the remaining magma, becomes more and more siliceous. For granitic and dioritic magmas, this follows from the fact that the minerals separate essentially in the order of their relative basicity, apatite and magnetite being followed by mica and hornblende, and these by the less siliceous feldspars, and finally by the siliceous feldspars and by quartz, if there be an excess of silica. During the later stages of consolidation, silica and salts of the alkalies and of lime come to be the main constitu-

ents of the solutions. This may be inferred, so far as silica and the silicates are concerned, from the position of quartz and the siliceous feldspars, orthoclase and oligoclase or albite, in the scheme of crystallization given above.

In general, the solutions escaping from a mass of crystallizing rock would carry with them the greater part of all the highly-soluble constituents of the original magma, among which chlorides, fluorides, carbonates, and sulphates may have been present in important amounts, and, if present, certain of these salts would increase the dissolving power of the waters in respect to silica, the metallic sulphides, and gold, so that the magmatic solutions could readily have produced the veins referred to them by the hypothesis. The quotation from Arrhenius given by Vogt[3] bears directly upon this point, as does Brögger's statement[4] of the order of formation of the minerals in the pegmatites of southern Norway, where the so-called mineralizing-agents, fluorine, chlorine, and boron, do not enter, to any great extent, into the constitution of the minerals formed during the first stages of solidification, but are found in considerable amounts in the minerals formed after the principal mass of the magma has crystallized.

The list of vein-minerals found in southeastern Alaska includes most of those recorded from the California mines, but the occurrence of tourmaline is frequent rather than rare, and considerable amounts of rutile are present in a certain set of veins near Juneau and in the Treadwell ores. In both instances the rutile is associated with albite and carbonates of lime, magnesia, and iron. The bearing which the presence of tourmaline and rutile may have upon the hypothesis of magmatic waters will be considered in some detail. (For a recent list of localities where ores are accompanied by tourmaline see *Zeitschrift für praktische Geologie*, vol. xii., 1904, p. 66).

When, in 1895, Mr. Lindgren[5] assigned the vein-forming waters of the Nevada City and Grass Valley districts to surface-waters penetrating the dioritic rocks and dissolving from them

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[3] *Genesis of Ore-Deposits*, by Posepny and others, p. 644 (1902).

[4] *Die Mineralien der Syenitepegmatitegänge der Südnorwegischen Augit- und Nephelinsyenite*, pp. 148 to 181 (1890).

[5] *Bulletin of the Geological Society of America*, vol. vi., pp. 221 to 224 (1894); also *Seventeenth Annual Report, U. S. Geological Survey*, Pt. II., p. 176 (1895-96).

metallic elements afterwards deposited during the return journey towards the surface, a difficult point to explain was "the absence of fluorine and boron-compounds which so often occur in ore-deposits in granitic rocks." The occurrence, in the Juneau region, of tourmaline which contains these elements may be regarded as favoring a source in igneous rocks, and in my belief their presence lends weight to the magmatic hypothesis.

Titanium oxide and albite occurring as original vein-minerals may point in the same direction, in the light of Daubrée's conclusions concerning the genesis of the titaniferous albite veins of the Alps. This distinguished synthesist produced crystals of titanium oxide by submitting titanium chloride vapor to the action of steam,[6] a procedure which was supposed to imitate natural conditions of deposition, indicated by the paragenesis of the three oxides of titanium—rutile, anatase, and brookite—in the Alpine veins. Daubrée therefore had no hesitation in suggesting "sublimations" as the active agents in forming the veins marked by the peculiar association of the minerals named with titaniferous hematite, quartz, albite, adularia, calcite, dolomite and siderite, mica, fluorite, tourmaline, etc. In this connection, he refers to the discussion by Élie de Beaumont of the relation between metalliferous veins and volcanic emanations, showing that in his own mind Daubrée regarded the sublimations as related to igneous activity.

Both Vogt and Lindgren[7] suggest that chloride or fluoride solutions, or vapors, have been important factors in the formation of topaz-cassiterite, scapolite-apatite, and tourmalinic gold-copper veins, the importance of which in the present connection is, that rutile is a common accessory mineral in the types of veins enumerated.

Bischof has shown the efficiency of sodium chloride solutions in transforming potassium feldspar to albite,[8] a fact which suggests the possibility that the metasomatic change of microperthite to albite which has taken place in the Treadwell deposit[9] may have been produced by the action of waters carrying common salt.

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[6] *Annales des Mines*, Fourth Series, vol. xvi., p. 130 (1849).

[7] *Genesis of Ore-Deposits*, Posepny, pp. 540 to 564 and 643 to 648 (1902).

[8] *Chemical Geology*, vol. ii., p. 410.

[9] Spencer, *Trans.*, xxxv., 505 (1904).

In the Juneau district the formation of albite as a vein-mineral, and as a metasomatic replacement in the wall-rock, is natural if the depositing waters were of magmatic origin, because the diorites of the region from which such waters would have been derived are essentially soda rocks. Likewise, the presence of rutile in some of the ore-deposits corresponds with unusual amounts of titanite in the intrusive rocks. That chlorine and possibly fluorine were also present in the parent magma may be properly assumed from the presence of abundant apatite in the diorites. On the magmatic hypothesis, either fluorine or chlorine may, therefore, well have taken part in the formation of the quartz-albite-rutile veins. In conformity with the ideas of de Beaumont and Daubrée, which have been especially elaborated along original lines by Vogt and Arrhenius, these and several other elements may play an important rôle in vein-deposition without entering into the constitution of any of the vein-minerals, and it is strongly suspected that sodium chloride may have been an essential component in the vein-forming solutions of this region.

In the veins of the Juneau district which have not yielded rutile or albite, boron and fluorine are present in the mineral tourmaline, and it is possible that chemical tests may reveal chlorides mechanically inclosed in some of the vein-quartz, as in the case of certain California veins investigated by Mr. Lindgren. Unfortunately, proper material for this determination is not at hand, but research along this line will undoubtedly be undertaken in connection with future studies of ore-genesis in southeastern Alaska.

The existence near each other of tourmaline-bearing veins, which, so far as observation shows, contain no albite and rutile, and others containing the latter minerals, without the former, is a feature the bearing of which is still unrecognized. No difference in relative age of the two types can be suggested, all the information at hand going to show the practical contemporaneity of the fractures in which they occur, so that it seems not at all improbable that the depositing solutions were of practically the same nature, the difference in the mineral aggregates in the two sorts of veins depending upon unlike conditions controlling deposition. An indication that this explanation may be true is the fact that the veins containing albite are in general

those inclosed by igneous rocks which have suffered considerable metasomatic changes, due to the vein-forming waters, while the albite-free veins occur typically in metamorphic sediments, or in igneous masses practically unaltered by the depositing solutions.

The above considerations seem to me sufficient to show that the magmatic hypothesis is adequate to account for the facts in southeastern Alaska. It remains, however, to show the inadequacy of the meteoric hypothesis before the suggestion of magmatic waters can be raised to the dignity of a theory. For the great metalliferous region bordering the Pacific coast it seems that the true theory of vein-genesis can be fully developed only by establishing with the greatest possible degree of accuracy the position which ore-deposition occupies in the geological history of the region. When this has been done I foresee the probability that a point of fatal weakness, in any attempt to explain the ore-deposits by waters derived from the surface of the earth, will be the impossibility of attributing to the action of downward-percolating waters any changes observable in the rocks, though such changes should be recognizable if the ascending waters by which the veins were undoubtedly deposited had been thus derived.

No. 22.

Genetic Relations of the Western Nevada Ores.*

BY J. E. SPURR, WASHINGTON, D. C.

(British Columbia Meeting, July, 1905. *Trans.*, xxxvi., 372.

CONTENTS.

PAGE

I. Introduction, ... 590
II. Tonopah, ... 591
1. General Geology, ... 591
2. Mineral Veins, ... 593
(a) Veins of the Earlier Andesite, ... 593
(b) Veins of the Tonopah Rhyolite-Dacite Period, . . . 594
(c) Veins Dependent upon the Oddie Rhyolite, . . . 594
(d) Alteration of Wall-Rocks, ... 595
(e) Source of Mineralizing Solutions, ... 596
(f) Summary of Genesis of Tonopah Ores, ... 598
III. Districts near Tonopah and Similar to It, ... 599
1. Gold Mountain, ... 599
2. Goldfield, ... 599
3. Bullfrog and Kawich, ... 600
IV. Comparison of the Tertiary Tonopah Ores with those of Other Regions, 601
V. Characteristics and Significance of the Vein-Group, ... 602
VI. Silver Peak Quadrangle, ... 603
1. General Geology, ... 603
(a) Stratified Rocks, ... 603
(b) Granitic and Aplitic Rocks, ... 604
(c) Dioritic Rocks, ... 606
(d) Tertiary and Quaternary Lavas, ... 606
2. Mineral Veins, ... 607
(a) Genetic Relations of the Ores of Mineral Ridge, . . 607
(b) Genetic Relations of the Great Gulch Ores, . . . 612
(c) Genetic Relations of the Silver-Ores of Mineral Ridge, . 613
(d) Genetic Relations of the Ores of Lone Mountain, . . 614
(e) Genesis of the Ores of the Southern Part of the Quadrangle, 615
(f) General Conclusions as to the Origin of the Metalliferous Ores, ... 616
VII. Comparison of Silver Peak with Other Ore-Deposits, ... 617
VIII. Conclusions Concerning the Silver Peak Type of Ores, . . . 619
IX. Magmatic Origin of Ores of Both Provinces, ... 620

I. Introduction.

The region here discussed is that part of western Nevada in which, during the last few years, discoveries of rich gold- and

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silver-ores have been made at Tonopah, Goldfield, and other camps. The special studies which have been made of the ore-deposits have chiefly to do with Tonopah and the older camp, Silver Peak, about 25 miles southwest of Tonopah. Other camps in the same region have also been visited.[1]

II. Tonopah.

1. *General Geology.*

Only those features of the general geology which are essential to the understanding of the ore-deposition will here be discussed. Tonopah is situated in a region of Tertiary volcanics, and the study of the general geology has chiefly to do with the nature, period, and effects of the different volcanic eruptions. The volcanic rocks comprise andesites, rhyolites, dacites (latites), and basalt. There are also present Tertiary lake-beds, mostly stratified tuffs derived from the volcanic outbursts. The structure and succession of these lavas indicate a varied history, comprising many volcanic eruptions, which brought forth showers of ash and pumice, or streams of lava. The volcanic activity was accompanied by movements in the crust, which produced tilting of the rocks and a very intense and complex faulting.

There are grounds for believing that beneath the Tertiary volcanics of Tonopah there is an older formation of Palæozoic limestone and intrusive granite. Such formations outcrop both to the south and to the north at frequent intervals. At Tonopah fragments of limestone and granite are among the blocks which were hurled out from the volcanoes at the time of some of the dacitic eruptions.

The oldest of the Tertiary volcanic rocks is an andesite which I have called the earlier andesite, to distinguish it from a subsequently erupted rock of similar composition. This earlier andesite, wherever found, is decomposed to a variable extent. From microscopic study it appears that the original fresh rock was a hornblende-biotite-andesite, the feldspar being typically andesine-oligoclase. In the present altered condition, no actual biotite or hornblende has been found, these minerals being represented by their decomposition-products,—quartz, sericite,

[1] I have described these camps in Professional Papers of the U. S. Geological Survey, soon to be issued.

pyrite, siderite, and hematite, sometimes chlorite and calcite. The feldspar is usually altered to quartz and sericite or quartz and adularia. As a result of the alteration-processes the whole rock is usually more or less completely altered to an aggregate which is composed of quartz and sericite, with usually some pyrite and siderite, and frequently adularia, kaolin, and iron oxides. Chlorite and calcite are not so common, but may be abundant. They indicate a process of decomposition different from the ordinary. As a rule the rocks may be divided according to their processes of decomposition into two classes: (1) quartz-sericite-adularia-pyrite-siderite rocks,—most abundant and most closely associated with the metalliferous veins; and (2) chlorite-calcite rocks,—not associated with the ores.

The next oldest rock is the later andesite. This is much like the earlier andesite, but is slightly less siliceous. It is often nearly fresh, and is in other places largely decomposed. The general process of decomposition is usually different from that of the earlier andesite. The phenocrysts are larger and more abundant than in the earlier andesite, and consist of biotite, augite, hornblende, and feldspar which is predominantly andesine-labradorite. In general the decomposition-products are quartz, chlorite, calcite, pyrite, and siderite. The later andesite overlies the earlier andesite and covers up the metalliferous veins which occur in the latter rock.

Younger than the andesites are a series of rhyolitic rocks (rhyolite-dacites or latites). These lavas differ slightly in composition among themselves and were erupted at different times during a single general period of volcanic activity. In the complete report upon this district,[2] several of these eruptions have been distinguished and separately mapped, but only three of these need here be mentioned. One of these, which I have called the Tonopah rhyolite-dacite, is a dense, glassy rock, occurring in intrusive masses and thin sheets. This rock contains porphyritic crystals of biotite, feldspar, and quartz in a glassy ground-mass. The most common feldspars are orthoclase and andesine-oligoclase. Near its intrusive contacts, this rock is often greatly silicified, the alteration having evidently been accomplished by hot-spring action succeeding the intrusion.

[2] Geology of the Tonopah Mining District, Nevada, *Professional Paper No. 42, U. S. Geological Survey* (1905).

Secondary quartz, pyrite, and sometimes siderite, are the chief results.

A dacite of later age and of somewhat different character is the rock which forms the hills around Tonopah. These eminences represent the columns of lava which rose from the abysmal regions to the surface. Near the contacts of these necks the intruded rocks are usually hardened and silicified and the cracks are coated with chalcedony.

A few of the volcanic necks consist of white siliceous rhyolite (Oddie rhyolite) of nearly the same age as the dacite necks. This rhyolite has a micro-granular ground-mass of quartz and feldspar, with porphyritic crystals of coarse quartz, orthoclase, and occasional plagioclase and biotite.

2. *Mineral Veins.*

(a) *Veins of the Earlier Andesite.*—The most important veins of the Tonopah district are in the early andesite and do not extend into the overlying rocks. Where the early andesite is not exposed at the surface the later rocks form a capping to the veins. This fact shows plainly that the veins were deposited before the eruption of the later andesite and immediately after that of the earlier andesite; indeed, there is every evidence that they were formed by ascending hot waters succeeding and connected with the earlier andesite intrusion, and that these waters had become inactive by the time of the later andesite. The openings which afforded channels for these ascending waters were sheeted zones in the rock. The rock was complexly fractured, apparently soon after cooling, and certain zones of maximum fracturing became the chief circulation-channels. These fractured zones have become veins, largely by a process of replacement of the rock. That the mineralizing agency was water is evident from the character of the vein and the nature of the alteration of the wall-rock; that its action was probably connected with the earlier andesite eruption is shown by the fact that it followed this, and, at least so far as mineralizing activity was concerned, was of limited duration, for its effects have not been discovered in the succeeding later andesite. It appears probable, therefore, that the mineralizing agents were volcanic waters, such as are usual among the after-effects of volcanic outbursts, and that they were hot and ascending.

In the primary sulphide ores, lying below the oxidized zone, the principal gangue-minerals are quartz, adularia, and some sericite, with occasional carbonates of lime, magnesia, iron, and manganese. The ore-minerals consist of sulphides of silver, antimony, copper, iron, lead, and zinc, in the form of stephanite, polybasite, argentite, chalcopyrite, pyrite, galena, and blende. A considerable quantity of silver selenide is also present, and gold in a yet-undetermined form. The remarkable thing about the metallic contents is the relative scarcity of the common elements and the abundance of the rarer ones.

The depth of oxidation in these veins is very irregular, dependent upon the relative perviousness of the overlying rocks. In the oxidized zone, horn-silver is abundant, with some bromides and iodides. Free gold has been deposited. The presence of limonite and black oxide of manganese is characteristic.

Pyrargyrite or ruby-silver and argentite frequently occur, coating crevices in primary ore, and in such cases are evidently of secondary deposition.

(b) *Veins of the Tonopah Rhyolite-Dacite Period.*—The veins connected with the earlier andesite constitute the principal class at Tonopah, but veins belonging to a later period are frequently found. These veins are associated with the Tonopah rhyolite-dacite intrusions and are dependent upon them, in the same way as the earlier andesite veins depend upon the earlier andesite. The veins of the Tonopah rhyolite-dacite period are characterized by irregularity and the lack of persistence, though their size may locally be considerable. The veins are barren or contain small quantities of gold and silver, except locally, where rich bunches of ore may occur. A characteristic of the rhyolite-dacite veins, to which there are, however, numerous exceptions, is the greater ratio of gold and silver in them as compared to that in the earlier andesite veins. These rhyolite-dacite veins are also plainly the result of ascending hot waters. The lack of definition and persistence as compared with the veins in the earlier andesite shows that at the time they were formed no definite fracture-zones were available as channels.

(c) *Veins Dependent Upon the Oddie Rhyolite.*—In one of the rhyolite volcanic necks (Mount Ararat) veins of a different character from those previously described have been formed. Near the contact of the rhyolite plug with the older rocks, the

rhyolite is peculiarly brecciated, showing great blocks jumbled together, with, however, rhyolitic matrix between. The dim outlines of these blocks and the nature of the matrix show that the breccia was formed when the lava was only partly rigid and in the process of cooling. This brecciation is confined to the zone near the contact. Many sharp fractures, chiefly parallel to the contact, are present in the rhyolite. These have been filled with vein-material, consisting of quartz, with ferruginous calcite containing some manganese carbonate. This gangue-material contains a little gold. These fissures and fractures plainly resulted from the continuation of the driving upward of the plug after consolidation was practically complete. The vein-fillings are the result of ascending hot waters which followed the channels thus opened and cemented them.

A consideration of these veins and their wall-rocks does not afford evidence of the mineralizing waters having contained anything beyond silica, lime and magnesian carbonates, and a trace of gold. The presence of iron is contrasted with the probable absence of iron in the waters which produced the veins in the earlier andesite.

(d) *Alteration of Wall-Rocks.*—In the altered phases of the earlier andesite there are all transitions between the typical quartz-sericite phase, in which calcite and chlorite are not abundant, and the typical calcite-chlorite phase, in which quartz and especially sericite are decidedly subordinate. Hence it has been concluded that these different phases are due to the chemical effects of the same mineralizing waters, which differed in nature as they penetrated to a greater and greater distance from the circulation-channels. Along these channels, which became veins, the rock was transformed by the deposition of silica, sulphides of silver, antimony, etc., gold, and selenides. The soda and magnesia, and part of the lime and iron, were removed. In the wall-rock near the vein, lime, iron, magnesium, and soda have been replaced by silica and potash. In the rocks more remote from the vein-channels, though the alteration has been complete, there has been no very great increase or decrease in the original elements.

From a study of these different effects of the mineralizing waters, it has been concluded that they were charged with an excess of silica and potash, together with silver, gold, antimony,

arsenic, copper, lead, zinc, selenium, etc. They were notably deficient in iron, but contained carbonic acid and sulphur, as well as some chlorine and fluorine. The presence of the two last-named gases is shown by some probably original silver chloride and by the presence of muscovite in the gangue, a mineral which is believed to crystallize almost invariably in the presence of fluorine.[3]

The later andesite is not altered as much as the earlier andesite, but is, however, locally greatly decomposed. From a study of the nature of this alteration, the conclusion has been drawn that the waters which produced it were highly charged with carbonic acid and sulphur, and that they contained magnesia and iron, and also probably lime, in considerable quantity. They were clearly hot-spring waters, as shown by the excessive carbonation and sulphuration, as well as the formation of sericite and talcose materials, uralite, chlorite, serpentine, zeolites, etc. Their chemical composition was quite different from that of those waters which altered the earlier andesite. From a study of the localization of the decomposition of the later andesite, it seems likely that it was due to the influence of solutions following the contacts of later intrusive rhyolitic rock.

(e) *Source of Mineralizing Solutions.*—The waters which produced the veins and the rock-decomposition in the early andesite were rich in silica and potash and poor in the other common rock-forming elements. They seem to have directly followed the earlier andesite eruption. Those that altered the later andesite were rich in magnesia, lime, and iron, and low in silica and the alkalies, and seem to have followed the eruption of rhyolitic rocks, especially the Oddie rhyolite. Both were hot-spring waters, which differed in their composition as much as the rocks which they accompanied. There is an apparent antithesis in each case between the composition of the erupted rock and the accompanying hot solutions. The earlier andesite, a rock of intermediate composition, was followed by the advent of waters rich in the elements characteristic of extremely acid rocks. The eruption of the Oddie rhyolite, a very siliceous rock, was followed by the advent of

[3] Doelter, *Chemische Mineralogie*, p. 161; and Brauns, *Chemische Mineralogie*, p. 247 (1896).

waters rich in elements characteristic of basic rocks and poor in the elements represented in the rhyolite. The exact explanation of this antithesis is a matter for future study.

There are two possible explanations of hot springs: one is that they are due to atmospheric water which has sunk down from the surface to such a depth that it becomes highly heated and then rises again; the other is that they are due to water which forms a part of the molten material in the earth's interior and which is concentrated and separated from the magma upon the cooling of a molten mass. Lavas which cool at the surface give off vast quantities of water-vapor, and the phenomena of contact-metamorphism, especially that connected with siliceous rocks, show that in depth similar water-vapor is expelled from cooling rock. It seems therefore impossible to escape the conclusion that at least some hot springs, the after-phenomena of volcanic activity, are due to magmatic water.

In the arid Nevada region there are, as a rule, no flowing surface-waters, the whole supply emerging from the ground as springs. These springs may be either warm or cold. The cold springs usually show two characteristics which indicate that they are of vadose or atmospheric origin: (1) they fluctuate with the season, and (2) they become more numerous in regions of greater precipitation and rarer in the more arid portions. The hot springs, however, so far as the writer knows, do not show these characteristics. They are notably associated with areas of volcanic rocks and they are often very vigorous in the heart of an arid region.

Volcanic activity has lasted in this province from the beginning of the Tertiary to within a few hundred years ago, but many of the hot springs which accompanied or followed the different manifestations of volcanic activity are now extinct. At Tonopah, waters ascending after several of the volcanic eruptions, mineralized and altered the formations through which they passed, and became extinct in a relatively short space of geologic time. It is difficult to explain the totally different composition of the waters of the different periods on the hypothesis that they were of atmospheric origin, and the antithesis pointed out between the contents of waters of different periods and the composition of lavas which they followed is equally difficult to account for on this hypothesis. A third

consideration is the peculiar combination of materials in the waters which produced the veins of the earlier andesite, especially the presence of unusually large quantities of the rare metals silver and gold, and unusually small ones of the commoner ones, copper, lead, zinc, and iron. Plainly some process of separation and concentration has furnished the noble elements contained in the mineralizing waters, separating them from the baser metals. A view concerning this same problem at the Comstock, expressed by von Richthofen,[4] appeals to me as an explanation of the Tonopah ores also. Von Richthofen pointed out that the volatile materials, chiefly fluorine, chlorine, and sulphur, given off during solfataric action, would extract from the cooling rock metallic substances of much the same character and proportion as those present in the Comstock lode, while ordinary waters would furnish primarily the more abundant metals, such as iron and manganese, and only small amounts of silver and gold.

(f) *Summary of Genesis of Tonopah Ores.*—The considerations pointed out appear to indicate the following conclusions.

The Tonopah district was during most of Tertiary time a region of active vulcanism, and probably after each eruption, certainly after some of them, solfataras and fumaroles, succeeded by hot springs, thoroughly altered the rocks in many parts of the district. At the surface, during these periods, the phenomena of fumarolic, solfataric, and hot-spring action were similar to those witnessed to-day in volcanic regions; but the rocks now exposed were at that time below the surface. The veins have cemented the conduits which were formed by the fractures due to the heavings of the surging volcanic forces below, and along which gases, steam, and finally hot waters, growing gradually cooler, were expelled, relieving the explosive energies of the subsiding volcanism. The water and other vapors, largely given off by the congealing lavas below, carried with them, separated and concentrated from the magma, metals of such kind and of such quantity as are present in the veins, together with silica and other materials. The nature of the metallic minerals in the veins is believed to have depended largely upon the particular magma whence the emanations proceeded.

[4] Cited in *Monograph III., U. S. Geological Survey*, pp. 19 to 20 (1882).

III. Districts Near Tonopah and Similar to It.

1. *Gold Mountain.*

The mining-district of Gold mountain, 4 miles south of Tonopah, has been prospected for several years, but has not developed into a camp of any importance. The rocks here are rhyolite, rhyolite-breccia, and tuffs, in which fracture- or breccia-zones have been formed, and have been transformed into veins by circulating waters. The vein-material is quartz, often chalcedonic, and the metallic mineral chiefly pyrite, which sometimes contains gold and sometimes silver. In some cases the veins contain gold only, while in others considerable silver is also present. Some of the richest ore is oxidized and occurs in pockets near the surface. From such ore, shipments have been made, but most of the veins are of low grade.

The rocks at Gold mountain are similar to the Tonopah rhyolite-dacite series of lava, breccias, and associated tuffs at Tonopah, and the characteristics of the Gold mountain veins are similar to those of the rhyolite-dacite veins at Tonopah. In both cases the veins, while they are locally strong, have not the regularity or persistence of the earlier andesite veins.

2. *Goldfield.*

I have visited Goldfield, about 24 miles south of Gold mountain, but I have not yet studied the geology thoroughly. The rocks, chiefly volcanic, consist of rhyolites, rhyolite tuffs, andesites, and basalts, all probably of Tertiary age. One andesite examined microscopically resembles the earlier andesite at Tonopah, and a specimen of basalt resembles the basalt of that district. The rhyolite also resembles the rhyolite of Gold mountain. The ores occur in both rhyolites and andesites, showing that the mineralization occurred subsequent to the eruption of both lavas. It is therefore possible that the Goldfield deposits are identical in origin with the later series of veins at Tonopah, which accompany the Tonopah rhyolite-dacite, although at Goldfield these veins are of vastly greater economic importance.

There is also a resemblance in the physical characteristics of the later Tonopah veins and the ore-bodies at Goldfield; in the latter, however, the quartz masses are still more irregular; the

outcrops may be roughly elongated, nearly circular or crescentic. The quartz is gray and jaspery and is due to the silicification of the volcanic rock, which is undoubtedly the work of hot springs. Had the rocks been strongly fractured we should have had more definite veins like those of the earlier andesite at Tonopah.

The greater part of one of these quartz reefs at Goldfield contains little or no gold, although pyrite is disseminated throughout. Frequently, however, ore-shoots of relatively small size occur, which are difficult to distinguish, except by assaying, from the barren portion. It seems probable that these pay-shoots represent the main channels of circulation, while the siliceous casings are the result of water soaking through the adjacent rock. The values of the ores are chiefly, sometimes entirely, in gold, but in some cases considerable silver has lately been found.

The sulphide ores lying beneath the oxidized surface-ores contain tetrahedrite which is highly auriferous. Tellurium is present, probably in the form of gold telluride. Bismuth sulphide is not uncommon. Free gold also occurs in these sulphide ores. In the gangue, barite is common, but not abundant.

3. *Bullfrog and Kawich.*

Since the opening up of Goldfield, more than a year ago, a number of promising new camps have been discovered in the neighborhood, especially to the south and east. Chief among these are perhaps the Bullfrog and the Kawich districts, the former of which lies 60 miles southeast of Goldfield; the latter 72 miles east. I have not yet visited these camps, but from personal correspondence I have obtained some idea of their nature. Oscar Rohn has sent photographs, samples and descriptions of the Kawich district, which indicate for this camp a close analogy to Goldfield, the ore-bodies occurring in similar rocks and being of the same character. Mr. Rohn reports that one of the principal formations at Bullfrog is rhyolite and rhyolite-breccia, which he regards as equivalent to lavas of the Tonopah district. The veins occur in part at least along fault- or fracture-zones in the volcanic rock. The gangue is chiefly quartz, and the values are gold and silver.

IV. Comparison of the Tertiary Nevada Ores with Those of Other Regions.

Among the nearest analogies to Tonopah yet described elsewhere are the contiguous mining-districts of Pachuca and Real del Monte, in Mexico.[5] These districts are similar to Tonopah in character and age of the wall-rocks (Miocene andesites); in the nature of the alteration of the rock near the veins (silicification near the veins, propylitic alteration farther away); in the structural character of the veins (splitting and reuniting); the general character of the ores (both oxide and sulphide), and of gangue (though adularia as a gangue-material and selenides as ores have not been recognized at Pachuca); and in the occurrence of the rich ores in bonanzas, which seem to be due to the intersection of transverse fractures with the main vein-zone.

Many other deposits in Mexico which have not been fully described seem, from their recorded characteristics, to be closely similar to Tonopah.[6]

Pachuca is about 2,000 miles southwest of Tonopah, but an analogous deposit lies 150 miles to the northwest,—the Comstock. The Comstock is similar to Tonopah in respect to the character and age of the rocks in which the lode lies (Tertiary andesite) and their "propylitic" alteration; in the nature of the gangue and ore; and in the occurrence of the rich ore in irregular "bonanzas." The chief distinction is that the Comstock consists of a single very strong lode, while at Tonopah there are a number of small ones.

Another region having many striking peculiarities in common with Tonopah lies about 400 miles due north of it,—the districts of Silver City and Delamar in southwestern Idaho.[7] These districts are similar to Tonopah in that the ores occur in Tertiary volcanics and are probably in both cases post-Miocene in age; to a striking degree in the character of the ores and gangue-materials; in the structural characteristics of the veins, which form a group knit together by branches; in the

[5] Aguilera and Ordoñez, *Boletin del Instituto Geologico de Mexico*, Nos. 7, 8 and 9 (1897).

[6] J. G. Aguilera, *Trans.*, xxxii., 513 (1901).

[7] Lindgren, Waldemar, *Twentieth Annual Report, U. S. Geological Survey*, Pt. III., pp. 107 to 189 (1898–99).

general character of the alteration of the wall-rock; and in the occurrence of the rich ores in irregular "bonanzas." The chief difference is that, in these Idaho districts, the wall-rocks are mainly rhyolite, and not andesite.

V. CHARACTERISTICS AND SIGNIFICANCE OF THE VEIN-GROUP.

The different mineral districts, mentioned above, exhibit a definite group of veins, characterized by the following features: They occur in Tertiary volcanic rocks of similar character in the different localities, being chiefly Miocene andesites or rhyolites. They constitute strong masses or veins which have as gangue essentially quartz with frequently a little calcite, while adularia, barite, rhodochrosite, or rhodonite may also be present in limited quantity. The ore is characteristically a silver-gold one, silver being usually predominant in the values in varying proportions, though the relative value may be reversed, and in some extreme cases either metal may occur with little admixture of the other. In any case the abundance of silver or gold, or both, in reference to lead, zinc, iron, etc., is characteristic. Silver sulphides, especially argentite, also stephanite and polybasite (together with ruby-silver), and gold, probably largely in a free state, are a distinguishing feature in the great majority of cases. Tellurides and selenides may also be present. Pyrite, blende, chalcopyrite, and galena are usually present in varying quantity. Where they become predominant the vein becomes relatively low-grade. Tetrahedrite, stibnite, and bismuthinite are also known to occur. The wall-rocks are much altered to quartz, sericite, chlorite, calcite, epidote, pyrite, etc., and sometimes to adularia. Frequently the rocks nearest the veins are chiefly altered to quartz and sericite; those farther away to the softer "propylitic" alteration, consisting of calcite, chlorite, pyrite, epidote, etc. The rich ores occur in irregularly outlined portions of the lode called "bonanzas," which are of limited extent, both horizontally and vertically, and are believed to have arisen as a consequence of the irregular intersection of transverse fractures or fissures with the main vein-channels.

Unquestionably the close relation between the different mineral districts mentioned shows a metallographic province, which in this case coincides with a portion of a petrographic prov-

ince.[8] It is probable indeed that the co-extension of the metallographic and petrographic provinces is greater than thus established. At many points along the belt of the petrographic province in the Andes of South America,—for example, in Peru[9] —veins are reported to have, so far as can be made out, a mode of occurrence, age, and composition similar to those of Mexico.

In that better-established portion of the metallographic province which comprises Mexico and Nevada, the ores occur in Miocene andesites in a great majority of cases. In occasionally recurring cases they appear in Miocene-Pliocene rhyolites which succeeded the andesites. The ores are believed to be due to the after-actions of the eruptions, in the shape of fumaroles, solfataras, and hot springs. Moreover, since these manifestations follow all volcanic eruptions, it is probable that the metals deposited by the after-processes owe their nature and amount to an unusual proportion of them in the magma with which they are genetically connected.

VI. Silver Peak Quadrangle.

Of quite a different class of ore-deposits from that described in the preceding pages are those of the Silver Peak quadrangle, whose northeastern corner is only about 10 miles west of Tonopah. The deposits of this quadrangle have been made the subject of a Professional Paper, to be published by the U. S. Geological Survey.

1. *General Geology.*

(a) *Stratified Rocks.*—Palæozoic limestones with slates and some quartzites are well represented in the area of the Silver Peak quadrangle. They belong entirely within the Cambrian and Ordovician eras. Most of our knowledge of the Palæozoic strata is due to the work of Messrs. Turner, Walcott, and Weeks, of the U. S. Geological Survey. The known fossils show the presence of strata belonging to the lower Cambrian, the upper Cambrian, and the Ordovician. The rocks, however, are characteristically considerably folded and faulted and frequently metamorphosed, and the series, which is several thousand feet

[8] Spurr, J. E., *Trans.*, xxxiii., 332 to 333 (1902); p. 295, this volume.

[9] Fuchs et de Launay, *Traité des Gîtes Minéraux et Métallifères*, vol. ii., p. 829 (1893).

thick, presents no very striking and constant lithologic differences. The detailed stratigraphy and structure, therefore, are still in some doubt.

In the district where the principal gold-mines are situated, near Silver Peak village, there is, below the fossiliferous Cambrian, a series of considerable thickness consisting of limestones and slates, with some dolomitic marble beds. This series has been intruded by numerous alaskitic sheets and by quartz veins. (Alaskite is a granitic rock composed essentially of quartz and alkali feldspar.) It has become largely schistose and gneissic.

No sedimentary rocks intermediate in age between the Ordovician and the probable Eocene have been found within the area of the quadrangle, but there are extensive and thick deposits belonging to the Tertiary. These Tertiary deposits flank the edges of the mountains and underlie in part at least the Pleistocene veneer of the valleys. They consist of soft shales, sandstones, marls, tuffs, volcanic breccias, etc., with interbedded layers of andesitic and rhyolitic lava. The thickness of the whole accumulation is very likely several thousand feet.

(b) *Granitic and Aplitic Rocks.*—Granitic rocks, intrusive into the Palæozoic strata, are well represented in the quadrangle, especially in three chief areas—in the northeast corner near Lone mountain, on Mineral ridge near Silver Peak village, and in a long belt running northwesterly across the southern part of the quadrangle. In the first-named region, near Lone mountain, H. W. Turner has found that the granitic rocks are chiefly true granites, composed of alkali feldspar and quartz, with some biotite and muscovite. The feldspar includes orthoclase, microcline, and albite.

In Mineral ridge, the interbedded slates and thin limestones have been thoroughly injected by siliceous granitic rock, mostly along the stratification, forming chiefly interbedded, more or less lenticular bodies, and often penetrating the intruded rock thoroughly and altering it to a schistose or gneissic condition. The prevalent phase of the intrusive rock is alaskite or quartz alkali-feldspar rock, having a granular texture like that typical of granite, which very frequently becomes coarser or finer (pegmatitic or aplitic). A frequent, but not common, facies of this alaskite is a siliceous biotite-granite like that at Lone mountain. On the other hand, the alaskite passes by gradual

transitions, by a diminution of the feldspar, into pure quartz veins (dikes), which have very much the same chemical and genetic relation to the alaskite that the alaskite has to the granite. The alaskite consists almost wholly of quartz and feldspar, the chief species of the latter having been determined as orthoclase, microcline, and oligoclase-albite.

The granite masses studied by Mr. Turner in the southern part of the quadrangle show a variety of different phases. In composition the rock varies from normal granite to alaskite on the one hand, and to quartz-monzonite or granodiorite on the other, the proportions of lime, soda, and potash being variable.

In connection with the granitic areas near Lone mountain and in the southern part of the quadrangle there are numerous aplitic dikes which clearly represent the later facies of the intrusions. They are mostly quartz-feldspar rocks or alaskites, more siliceous than the related granites. At Mineral ridge this rock is the predominant type, but in the other regions is subordinate to the granite proper. In many phases of these alaskitic rocks a tendency is seen under the microscope for the feldspar and quartz to segregate in bunches, which are irregular or more frequently elongated. These segregations increase in size until they are conspicuous to the naked eye, and by further enlargements quartz masses (veins), often feldspathic, are formed. Such granitic and magmatic quartz is found in all the granite areas, but in the siliceous alaskitic area of Mineral ridge occurs in great quantities, in thick veins or lenses. The various closely related phases of the granitic intrusions are regarded as variations from a single general granitic magma.

It is probable also that the different bodies present represent essentially a single period of intrusion. In the Silver Peak quadrangle the granitic rocks were intruded subsequent to the deposition of the Palæozoic strata and previous to the Tertiary sediments and lavas. The date of their intrusion is therefore post-Ordovician and pre-Tertiary. A short distance north of the Silver Peak quadrangle granitic rocks similar to those at Silver Peak are probably intrusive into Triassic and Jurassic strata at several points in the Pilot, Excelsior, Ellsworth, and Star Peak ranges.[10]

[10] J. E. Spurr, *Bulletin No.* 208, *U. S. Geological Survey*, 2d ed., pp. 102, 103, 109 (1903); and G. D. Louderback, *Bulletin of the Geological Society of America*, vol. XV., pp. 317, 336 (1903).

The work of Mr. Turner has shown that the granitic rocks in the southern part of the Silver Peak range cross Fish Lake valley, which lies west of the range, and are represented in the White Mountain range, which is separated from the Sierra Nevada only by Owen's Valley. This adjacent portion of the Sierra Nevada is made up almost wholly of granitic rocks, consisting mainly of granodiorite and granité, and the date of their intrusion has been fixed as in the epoch known as post-Jurassic.

It appears probable, therefore, that the granitic rocks of the Silver Peak quadrangle and of various other ranges of western Nevada are similar in general nature, age, and origin to the granitic rocks of the Sierra Nevada, and are late Jurassic or early Cretaceous in age.

(c) *Dioritic Rocks.*—Small dikes of diorite are abundant in the Silver Peak region. They are almost always more or less altered, sometimes completely. In their fresh form they consisted essentially of feldspar and hornblende in varying proportions, but by alteration they have become a mass of secondary products. They are thus conveniently designated by the field-name of greenstones. The alteration-products include chlorite, quartz, calcite, zeolites, epidote, zoisite, kaolin, talc, biotite, etc.

These dioritic rocks appear, from Mr. Turner's mapping, to be associated with the areas of associated granitic rocks. In point of age the dioritic rocks are always younger than the granitic rocks, which they frequently cut. When they occur associated with the aplitic rocks (alaskites) they are also younger than these, and, as Mr. Turner has found, they are younger than the quartz veins of Mineral ridge, which I have determined to be the siliceous extreme of the alaskitic injection. These greenstone dikes are older than the Tertiary rocks, since they are not found in them. Therefore, the only direct evidence of their age is that they are post-Ordovician and pre-Tertiary. The apparent association with the granitic areas and the limited quantities of the diorite, whose habit and amount approximate those of the alaskites, suggest, however, that the dioritic rocks may be a later manifestation of the granitic intrusions.

(d) *Tertiary and Quaternary Lavas.*—In the area under consideration, lavas were erupted in large quantity during most of the Tertiary, and the volcanic activity continued into the Qua-

ternary. The knowledge of the Tertiary lavas of the Silver Peak region is entirely the result of the work of Mr. Turner, who has mapped the different rocks separately and has distinguished and studied rhyolites, andesites, basalts, and some dacites. These lavas seem to have been repeated at different periods.

2. *Mineral Veins.*

(a) *Genetic Relations of the Ores of Mineral Ridge.*—The auriferous quartz-ores of Mineral ridge are economically the most important in the quadrangle, and some of the mines here have had a considerable production. The Drinkwater mine and some adjacent mines make up the most important group.

The typical auriferous quartz of Mineral ridge is white and crystalline and is seen under the microscope to be crowded with liquid inclusions. Its appearance is that of the characteristic gold-quartz found in so many districts in the world. Occasionally this quartz contains original muscovite and, rarely, original chlorite crystals. Contemporaneous sulphides are sparsely disseminated, principally pyrite, more rarely galena. Occasionally copper pyrite has been observed. The quartz throughout contains gold and a little silver, the proportion of the latter to the former being about 1 to 100. The gold is finely disseminated in a free state through the quartz and is also contained in the scattered sulphides. It is estimated that about 87 per cent. is in the free disseminated form and the remainder in sulphides. The gold-values are irregularly concentrated into certain groups of quartz lenses and certain lenses within these groups. Thus, in certain portions, it is high-grade, while in others it is low-grade or nearly barren.

The quartz lenses are intimately associated with alaskite intrusions, one not occurring without the other. Petrographically, typical quartz and typical alaskite form two ends of a rock series, between which every gradation is abundantly represented. The alaskite becomes quartzose and passes to a state where it contains quartz blotches and veinlets and so gradually passes over into typical vein-quartz. Nearly every quartz lens which has been mined or prospected shows in places considerable feldspar mixed with the quartz. As a rule, the gold-content grows rapidly less with increasing feld-

spar, although occasionally feldspar-bearing rock carries good values. In one place primary free gold has been found in pegmatite.

It was long ago recognized that granite rocks (which family includes the alaskites) had originated from magmas essentially different in nature from those which form the more basic plutonic rocks and from those which produce surface-lavas. This recognition was due to the discovery of many minerals in granite which cannot be formed from dry melts. Moreover, the relative order of crystallization of the chief granitic minerals is not the order of their relative fusibility, showing that the different materials were not held in the fluid state by the power of heat alone. All the granitic minerals have been artificially formed in the presence of mineralizers, such as water, fluorides, boron compounds, tungstic acid, etc., at a relatively moderate heat, but most of them cannot be formed by cooling from a dry melted mass. The contact-metamorphism which intrusive granitic rocks exert upon the rocks which they cut is of such a character as to show the presence of mineralizers. Minerals like tourmaline, scapolite, muscovite, etc., frequent in the contact-metamorphic aureoles of granites, testify to the emanation of boron, chlorine, fluorine, acid, water, etc., from the consolidating granitic magma. From these and other considerations it is probable that granite has crystallized at a relatively low temperature (compared with that of less siliceous igneous rocks), and that it has remained mobile below the fusing-point of most of the granitic constituents on account of the intermixture of water and other mineralizers. It is likely that water was one of the most abundant and efficient factors in these processes. The quantity of water in a magma has never been even approximately determined. Scheerer[11] estimated it as between 1 and 50 per cent., but believed that the actual quantity approached much nearer the minimum than the maximum of these figures.

Microscopic study of thin sections of the alaskite of Mineral ridge shows that the crystallization of the rock was slow and interrupted. Two distinct periods or generations of crystals are always represented. In different sections the nature and

[11] *Bulletin de la Société Géologique de France*, Second Series, vol. iv., p. 490 (1846–47).

relative amounts of the minerals belonging to each generation vary greatly, but the following observations apply to all cases:

1. Quartz is usually absent from the first generation, or if present is subordinate. In the second generation it is always predominant. In some cases the first generation is made up entirely of feldspar and the second entirely of quartz; but the separation is usually not so marked, some of the feldspar crystallizing with the second generation together with the predominating quartz.

2. Microcline is almost always of the second generation.

3. Albite and oligoclase-albite occur generally in both the first and second generations.

4. Zircon and pyrite have been noted included in the minerals of the second generation, but not in those of the first.

In some cases the rock is almost entirely made up of crystals of the first generation, with the second generation represented in a very subordinate way. Other sections show the first generation only as scattering idiomorphic crystals, with the second generation making up the general area. In most cases, however, the division is fairly equable.

The chief lesson taught is that the quartz is slightly, but distinctly, younger than the feldspar. It is frequently segregated into irregular chains of grains, which lie between bands of more feldspathic material.

In nearly every section muscovite is present, generally in fine fibers. This muscovite in many cases is plainly an alteration-product which has formed at the expense of feldspar. It is, however, only the feldspars of the first generation which have been thus altered, while those of the second generation are clear. From study of numerous sections, three general points in regard to the muscovite are learned:

1. The microcline is almost always clear and subsequent to the muscovitization.

2. The quartz is almost always clear and subsequent to the muscovitization, but sometimes incloses fibers and blades of muscovite.

3. The orthoclase and striated feldspars (chiefly albite and oligoclase-albite) are in part muscovitized and in part clear, as is natural from their belonging to both generations.

From this it appears that a partial alteration of the feldspar to muscovite took place when the magma was partly consolidated, and before the deposition of the remainder of the magma, which formed the second generation.

These observations show that the crystallization process of the alaskite was slow, so that in many cases the magma became filled with contiguous idiomorphic feldspar crystals of the first generation, the interstices between which were filled with residual fluid. The mass composed of the first generation of crystals was sometimes rigid enough to be partly cracked and fissured. In these cracks and fissures, as well as in the interstitial spaces between the crystals, the residual fluid solidified. Study indicates that many of the fissures were formed by contraction consequent upon partial consolidation; others seem to have been due to movements brought about by pressure. Thus the quartz (which makes up always the chief part of the second generation), besides forming as intergranular quartz within the unbroken alaskitic fabric, filled the small fissures, and collecting in larger masses formed by itself on a small scale an independent intrusive in nearly the same sense as the alaskitic magma had done. We may logically conclude that this quartz left, upon consolidation, a residue which was still finer grained and more aqueous.

The ore-deposits are lenses of such magmatic quartz, which have various dimensions, as seen both on horizontal and vertical planes. These lenses are most abundant along certain zones in the intruded formation and overlap on one another. They disappear by wedging or by forking and by splitting into two or more branches. These lenses are original, and not fragments of larger dike-like bodies which have attained their form as a consequence of shearing. The wedging-out of the lenses is not attended by evidence of unusual movement; moreover, the phenomena of splitting and uniting forbid the assumption that the form is not primary.

In the chief mines of the district the formation of ore-minerals subsequent to the primary consolidation of the quartz lenses has taken place on an unimportant scale. Occasionally, however, some later precipitation has taken place. Along cracks in the quartz, frequently near the contact of the quartz with decomposed greenstone (altered diorite) dikes, subsequent

vein-material has formed, having a gangue of quartz with some calcite and chlorite, and carrying pyrite and galena. The inference is that subsequent to the first or primary deposition of minerals, and subsequent to the intrusion of the diorite, minerals were again deposited along cracks in the original quartz. These minerals are the same as those first deposited, and might be thought to be due to subsequent concentration, the material being derived from the first-formed minerals, and simply concentrated by subsequent circulating waters. This perhaps has sometimes been the case, but in one mine where the subsequent ore is economically important (the Mary mine), the amount of the subsequent deposition is so large as to suggest a fresh and independent supply of material. The phenomena in the Mary mine indicate the work of ascending waters, and these new solutions must have had a composition much like that of the solutions from which the primary ore was deposited.

The close association of the diorite dikes with the quartz-alaskite bodies, and frequently with the subsequent ores, easily leads one to the hypothesis that this subsequent mineralization was dependent on the diorite; but most of the diorite dikes have no later ores in their vicinity, and in the mine where the largest deposit of subsequent ore was noted (the Mary) there is no diorite.

The general conclusion is that in this district a series of shaly limestones have been intruded by a highly siliceous alkaline magma. From this magma crystallized principally feldspar and quartz, the consolidation of the feldspar in general preceding that of the quartz. The local phenomena indicate that the crystallization was practically all accomplished subsequent to the injection. This crystallization, however, was slow, so that the residual quartz was, before its final consolidation, in part drawn off into large and small reservoirs, and so could play the rôle of an independent intrusion. A process of magmatic differentiation by partial crystallization is here proved.

That the lenses are the fillings of cavities which were present in the schist is out of the question. The parallelism of the schistosity with the curving walls of the lenses shows that the intrusion filled spaces which it itself created. The lenticular form of these alaskite and quartz masses (including the

ore-bodies) is like that of the masses of pegmatite and pegmatitic quartz which have been observed in many places in schists near intrusive granitic contacts. I believe that this form is the normal one for attenuated, aqueous, but still viscous, granitic material, injected into schists. The fact that the same characterizations apply as a rule to the alaskite lenses and the quartz lenses, indicates that the alaskitic fluid must have been much the same as that of the quartz, both being less viscous than that which has formed the true granite, which neither in this quadrangle nor in similar provinces is accustomed to form lenticular intrusions, but rather bold and well-defined dikes and sheets of which all the ramifications are easily traceable.

After the last crystallization of the intrusive alaskite and quartz, diorite dikes were injected, and, probably directly afterward, relatively thin aqueous solutions circulated along cracks and produced a subsequent mineralization, not approaching, however, in commercial importance (in this especial district), the primary mineralization. The brittle quartz of the lenses having been cracked offered the best channels, and here the subsequent mineralization took place, generally under the relatively impervious schist hanging-walls, indicating ascending waters.

For various reasons it is believed that these subsequent mineralizing solutions represented a residue from the granitic eruptions, more aqueous than that from which the primary quartz crystallized.

(b) *Genetic Relations of the Great Gulch Ores.*—One of the gold-mines of Mineral ridge displays, at first examination, a different character from the general type which has just been discussed. At the Great Gulch mine the general geology is, for the most part, like that of most of the typical gold-ores of the district. The country-rock is a thin-bedded limestone-slate, considerably altered and schistose. Alaskite and quartz, frequently feldspathic, occur in interbedded lenses in the schist. The ore is auriferous arsenopyrite, which occurs in solid streaks of all thicknesses up to 1 or 2 ft. It is distinctly later than the quartz, but the larger streaks are noticeably associated with the alaskite and quartz lenses, especially with the latter. The hanging-wall of quartz lenses is an especially favorable locality.

Here, fracturing has occurred subsequent to the intrusion of the primary alaskite and quartz. Along the channels thus formed ascending waters arose and deposited sulphur, iron, arsenic, and gold. The period of this mineralization is uncertain from the local data, but from the resemblance of the phenomena here to those of the subsequent mineralization in the Mary mine of the Drinkwater group, it is probable that the ore in the two cases has a similar origin.

(c) *Genetic Relations of the Silver-Ores of Mineral Ridge.*—On the periphery of the gold-quartz district of Mineral ridge there are at several points ores which contain more silver than gold. The chief of these are at the Pocatello and Vanderbilt mines. The general geology here is like that of the Great Gulch mine. Alaskite and quartz lenses are intrusive into a schist which represents an altered shaly limestone. Greenstone dikes and sheets are present, following especially a zone of quartz lenses. Near the greenstone the quartz is frequently cracked, broken, and mineralized, and in these cracks the silver-bearing ore has been deposited. The most characteristic mineral is a mixed sulphide and oxide containing copper, antimony, silver, and gold.

Here the schists were first injected by a siliceous magma which crystallized as alaskite and quartz. Basic dikes were subsequently injected, which followed along the zone of quartz and alaskite lenses, because here fracturing was more easy on account of the greater brittleness of the materials. The intrusion of the diorite produced considerable additional fracturing in the quartz. Along the cracks thus produced mineralizing solutions circulated and deposited the ore. The whole history indicated is analogous to those cases of mines of the typical gold-quartz type which show notable subsequent mineralization, although the character of the ore is somewhat different in that more silver and copper in proportion to gold are present.

In other deposits on the periphery of the Mineral ridge auriferous quartz district there are ores which have the same type of metallic minerals as in the Pocatello and Vanderbilt group, but which have formed by replacement of a dolomitic marble which overlies the schist formation in which the gold-bearing veins lie. In these cases the inclosing quartz of the vein is contemporaneous with the metallic minerals, instead of being antecedent to them as in the above-described silver-mines.

The mineralization in all these silver-mines seems to differ from the subsequent mineralization described in the case of the gold-mines and prospects, in the presence of more silver and copper; otherwise the facts are not unfavorable for regarding all of this subsequent mineralization as belonging to the same period. I desire to put forth here, as a plain hypothesis, an idea which has been arrived at by considering and reasoning from the distribution and character of ore-deposits throughout the quadrangle, The hypothesis is, that solutions of granitic origin have deposited predominantly gold in the granite or in rocks silicified by the metamorphic effect of the granite, and that in or near calcareous or dolomitic rocks more silver and copper were deposited from the same solutions, the difference being due to the different precipitative influence of the wall-rocks.

(d) *Genetic Relations of the Ores of Lone Mountain.*—The Lone Mountain group of mines are all situated in Palæozoic limestones, dolomites, and shales which have been more or less metamorphosed by intrusion of granitic masses. Metamorphism is most intense near the contact, and fades away gradually as the distance increases. The limestones and dolomites are changed into marble, the shales into hornstones and schists, with the development of typical metamorphic minerals. The veins characteristically follow the stratification of the sedimentary rocks. Where they thus occur along bedding-planes these planes have evidently been the sites of differential movement, producing crushing and greater openness. More rarely the veins occur in cross-cutting shear- or fault-zones. In one type of ores, the black mineral containing copper and antimony, described in the case of the silver-mines of Mineral ridge, occurs, together with galena and pyrite. This mineral is similar to that which has been described under the name stetefeldtite, and will be referred to under this name in the present article. Copper, silver, and gold are present in these ores. The ores of another type are characterized by typical contact-metamorphic minerals as gangue, chiefly epidote and garnet. In this type the metallic minerals are magnetite, specular iron, pyrite, chalcopyrite, galena, gold, and silver. In another type a quartz gangue contains a small amount of stetefeldtite, with galena, free gold, and a little copper. In another type the primary ore is galena,

now largely altered to carbonate. In general there is a strong likeness among the different ores of this district.

From their location and the nature of their gangue the ore-deposits in the Lone Mountain district are plainly connected with the metamorphism of the sediments produced by the granite. At the time of the granite intrusion siliceous solutions emanated from the hardening mass and penetrated the surrounding sediments, which were thus recrystallized and metamorphosed. Such solutions circulated most vigorously along openings which had been formed by the intrusion. These openings were chiefly along bedding-planes, sometimes along cross-cutting shear-zones. Along them circulating granitic waters deposited quartz and metallic minerals, forming the veins.

(e) *Genesis of the Ores in the Southern Part of the Quadrangle.* —In the southern part of the quadrangle the ore-deposits are all prospects, no paying deposit having yet been discovered. One type of deposits consists of quartz veins of granitic origin, similar to the primary quartz of the Mineral Ridge district. These quartz segregations, however, are small in quantity and unimportant economically. As in the Mineral Ridge type, they contain some gold and very little silver. Other quartz veins of a different type follow shear-zones in granite. The quartz contains pyrite and gold, and the wall-rocks are altered. The resemblance of these veins in composition to the magmatic quartz veins of the first type leads to the belief that this second type also is due to siliceous residual solutions derived from the consolidation of the granite, which have circulated along available channels in portions of the granite which had already consolidated. Another type of veins occurs in calcareous and argillaceous sediments near the contact of the granite. The gangue is chiefly quartz, the metallic minerals chiefly stetefeldtite, galena, copper, pyrite, etc. The values are chiefly in silver with some gold. The country-rock consists of metamorphosed sediments containing typical contact-metamorphic minerals. Veins of this type follow fracture-zones, and along such a zone vein-formations may outcrop at intervals for short distances. In one case veins of this type in calcareous strata lie apparently along the same fracture-zone as auriferous quartz veins, of the second type above described, which lie in granite, the fracture-zone

crossing from the granite into the intruded rock. The fact that along what seems to be the same great fracture-zone the ores are of different types in the granite and in the intruded sediments, suggests that they were probably formed by the same solutions, and the different character of the veins is assumed to be due to the different character of the wall-rock.

(f) *General Conclusions as to the Origin of the Metalliferous Ores.*

An intimate inter-relation has been recognized for all the metalliferous ores of the quadrangle, and all have been traced to the consequences of one event, namely, the intrusion of granitic rocks into Palæozoic sediments in probably post-Jurassic time. This district is favorable for such determinations as have been made, since the granitic masses are small and the grouping of the ore-deposits around them is therefore more evident than in a region, like the Sierra Nevada, where the masses of granite are vastly larger.

The ore-deposits may be divided into the two chief groups:

1. Bodies of auriferous quartz, probably separated out in gelatinous form from alaskite, during the process of crystallization, and of the same age and nature as the intergranular quartz of granite and alaskite. In such quartz bodies gold is in places segregated in commercial quantities.

2. Quartz veins due to replacement or impregnation of crushed material along fracture-zones by siliceous solutions more attenuated than those described above and residual from the crystallization of the magmatic quartz of the first type. These solutions were probably in various degrees of dilution by magmatic water. Such deposits were formed chiefly along movement-zones following bedding-planes in the intruded strata; also in cross-cutting movement-zones in the strata, and to a less degree in the granites. They were formed contemporaneously with the recrystallization and contact-metamorphism of the sediments under the influence of the granite intrusion. They are more or less typical quartz veins in the pure carbonate rocks and in the granites, but in the argillaceous rocks the quartz is often intermixed in various degrees with metamorphic silicate minerals, such as garnet, epidote, etc. The metallic elements present are principally silver, gold, lead, arsenic, antimony, copper, iron, etc., in various combinations. There is

more gold in the granite, more silver and lead in the intruded strata. In the granite the metallic mineral is mostly pyrite, sometimes arsenical. In the sedimentary strata the characteristic metallic minerals are the altered sulphide containing silver, copper, and antimony, which we may provisionally call stetefeldtite, and galena. The different character of the metallic minerals is believed to be largely due to the wall-rocks, which have precipitated certain things from solution. Aside from the quartz the nature of the gangue is also believed to be chiefly due to the nature of the walls.

In all the types of ore-deposits studied, the character of the solutions is believed to have been highly siliceous and alkaline, with mineralizers, such as fluorine, boron, etc., present, but in a limited amount. The presence of gold and silver and other metals is sufficiently explained by the composition of solutions such as described, in which the necessary solvents are present.

VII. Comparison of Silver Peak with Other Ore-Deposits.

Fifty miles northeast of the northeast corner of the Silver Peak quadrangle is the Belmont district, at one time productive, but long since abandoned. The ore-deposits consist of quartz veins which occur in the immediate vicinity of an intrusive mass of granite. From some microscopic work done by me[12] on this granite, it appears that magmatic solutions have been active, producing quartz and muscovite at the expense of the orthoclase in the intrusive rock, and altering the siliceous limestone of the wall-rock to jasperoid and mica-schist. The mineral-bearing quartz veins, it was suggested, were probably contemporaneous with those which were found to occur in irregular form within the intrusive rock, and which were held to represent the final product of the magma. In these quartz veins the metallic minerals are chiefly stetefeldtite and some lead, copper, and iron.

In the Toyabe range there are numerous ore-deposits, of which the chief ones lie near Austin, about 65 miles north of Belmont. S. F. Emmons has described many of the deposits, which in nearly every case consist of white quartz veins carrying metallic sulphides. In the vicinity of Austin the veins are

[12] *American Journal of Science*, Fourth Series, vol. x., No. 59, p. 355 (Nov., 1900).

mainly in granite. In other parts of the district, however, the veins occur in the stratified rocks. In some of the veins the chief silver-bearing mineral is a mixed sulphide of antimony, as is the case in the neighborhood of Belmont. There is probably here an intimate connection between the metalliferous quartz veins and intrusive rocks.

About 15 miles east of the eastern edge of the Silver Peak quadrangle is the Southern Klondike district, which I have visited and studied briefly. At this camp the main country-rock is Palæozoic limestone, which is intruded by a long, dike-like mass of siliceous granitic rock, of a composition similar to alaskite. The rock as a whole is closely related to that which I described from Belmont, and also to the alaskite of Mineral ridge at Silver Peak. Occasionally there are in the igneous mass small segregated portions of pure quartz, in which bunches of pyrite and, more rarely, galena occur. The limestone near the contact has been altered to hornstone containing epidote, zoisite and other characteristic products of contact-metamorphism. Not many yards from the contact, in the altered limestone, is a quartz vein which follows parallel to the contact closely for a mile or more, and carries scattered values of silver and gold. The minerals contained are chiefly galena and pyrite, with small bunches of the rich black copper-silver sulphide or stetefeldtite, which has been described as characteristic of those veins in the Silver Peak quadrangle which are near the contact of the intrusive granite, but not in the granite itself.

All these mineral districts are closely similar. All the ores have evidently originated as the result of the intrusion of granitic bodies into Palæozoic sediments, and in all cases the ore-deposition was associated with contact-metamorphism. The granitic and alaskitic rocks which make up these intrusive bodies are similar in those districts which I have examined, namely, Silver Peak, Southern Klondike and Belmont, and, from Mr. Emmons's description, in the Toyabe range.[13]

In the three districts which I have examined there are similar peculiarities of the intrusive rocks, notably the segregation of small contemporaneous quartz masses within the rock, and the alteration of the feldspar to muscovite by magmatic processes.

[13] *Geological Exploration of the Fortieth Parallel*, vol. iii., p. 324 (1870).

In the Sierra Nevada, associated with the granitic intrusions, are auriferous quartz veins whose formation immediately succeeded the granitic eruption. The relation between these quartz veins and the granite has long been noted.[14] Recently Mr. Lindgren has adopted the hypothesis that the solutions which deposited the veins were of magmatic origin. These California gold-quartz veins are characterized by the common occurrence of albite as a gangue-mineral.[15]

VIII. Conclusions Concerning the Silver Peak Type of Ores.

The general conclusion is that the Silver Peak deposits are part of a larger province, which is represented more abundantly in the Sierra Nevada of California, with only outlying smaller areas in adjacent portions in Nevada. All the ore-deposits of this province seem to owe their existence to the intrusion of the post-Jurassic granite. The ores of this province have been concluded to be due to siliceous solutions, which were due to the crystallization of the granitic rocks. These solutions deposited the minerals they contained (silver, gold, etc.) along fractures or shear-zones or other channels, thus forming the typical gold-quartz veins of the region. In Nevada these solutions formed, where the wall-rock consisted of the calcareous strata intruded by the granite, a type of noble silver-gold veins (that is, veins often containing a comparatively small proportion of the baser metals) characteristic of this period.

This metallographic province appears to be most typically developed in California, for which reason we may call it the California province, while the province characterized by the ores in Neocene lavas is best represented east of the Sierra Nevada in the State of Nevada, and may therefore be called the Nevada province. In western Nevada the Nevada province

[14] Whitney, J. D., *The Auriferous Gravels of the Sierra Nevada*, p. 353 (1880). Kemp, J. F., *Ore-Deposits of the United States and Canada*, 3d ed., p 370 (1900). Lindgren, W., Gold-Quartz Veins of Nevada City and Grass Valley, *Seventeenth Annual Report, U. S. Geological Survey*, Pt. II., pp. 175 to 176 (1895–96).

[15] *American Journal of Science*, Second Series, vol. xxviii., No. 83, p. 249 (Sept., 1859); and Ransome, F. L., *Mother Lode Folio*, No. 63, *U. S. Geological Survey*, p. 8 (1900).

overlaps upon the California province, and along this overlap the ore-deposits belonging to one group are superimposed upon the other. The Nevada province is coextensive with the appearance of Neocene andesites and rhyolites at the surface, the California province with the appearance at the surface of post-Jurassic granitic rocks. Where, as in western Nevada, these granitic rocks and the strata which they intrude are exposed by erosion in patches lying in the midst of Tertiary volcanics, we may have veins belonging to the different periods very close together.

IX. Magmatic Origin of Ores of Both Provinces.

According to the previously expressed conclusions, all the ore-deposits of this rich region of Nevada can be referred to two chief periods of intrusive igneous activity. The various ore-deposits discussed appear to be genetically connected with one or the other of these two great periods. In both cases the mineralization has been ascribed, as the result of close study, to the final processes of rock-solidification subsequent to intrusion, the residual solutions and gases resulting from consolidation having been the agents which produced the mineralization. The metals also are in all cases considered to have been derived, together with the mineralizing solutions, from the respective magmas. In this whole district, therefore, the effect of the concentrating action of ordinary circulating ground-water does not enter perceptibly into our conclusions, and so far as we yet know it is negligible, except for some minor effects in rearranging the ores of the oxidized zone.

No. 23.

Are the Quartz-Veins of Silver Peak, Nevada, the Result of Magmatic Segregation?

BY JOHN B. HASTINGS, DENVER, COLO.

(British Columbia Meeting, July, 1905. *Trans.*, xxxvi., 647).

CHIEF among the varied problems facing the mine-manager is that of vein-structure and origin, which is highly important as a guide to successful discovery and development. If metalliferous deposits can be traced to the intrusion of waters along definite lines, then is there something tangible for him to study. But when he is told by a geologist that metalliferous deposits are due to some other cause, like magmatic differentiation, while not perhaps discouraged, he is impressed with a vague sense of new worlds to be conquered.

In 1897, while manager of the War Eagle mine at Rossland, B. C., where, previously, the ore-bodies had not been supposed to occur as veins, I suggested to visiting members of the Canadian Geological Survey that, perhaps, the structure of the pyrrhotite-bodies of that mine, which had been proved to occur along well-defined fractures, might throw some light on the similar deposits of Sudbury, then held to be basic aggregations from the original magma. Later investigation has at least provoked discussion of this last deduction, questioning its correctness and suggesting that, perhaps, the deposits are actual veins.

The following extract from a paper by J. E. Spurr[1] is quoted, because it sets forth Mr. Spurr's theory of the quartz-occurrences of the Silver Peak mines, which will be discussed in this article. It also graphically describes the attendant geological features.

"The Drinkwater group of mines, which is the most important part of the Blair gold properties, and which has produced practically all of the million dollars' worth of ore, as above stated, may be taken as typical of the gold-veins which, though widespread and numerous, show a wonderful similarity of character. On the surface two adjacent veins outcrop, the Crowning Glory and the Drink-

[1] Ore Deposits of Silver Peak Quadrangle, *Bulletin No.* 225, *U. S. Geological Survey* (1904).

water, the former the larger, the latter containing the greater quantity of good ore. The quality of the ore still left standing (only the richer portions having been removed for milling) has been more or less carefully determined a number of times. . . . .

"Geologically, the veins of the Blair mine are interesting. Properly speaking, they are hardly veins, but flattened lenses of quartz occurring in a definite zone 100 ft. or more in thickness. The lenses wedge out and disappear both horizontally and vertically, and their place is taken by overlapping lenses. The wall-rock is a schist, derived chiefly from the metamorphism of an original limy shale or limestone. Frequently, also, the wall-rock is a very siliceous granitic rock (alaskite), made up essentially of quartz and feldspar. This alaskite occurs in the schist in lenses similar to the quartz. There is, moreover, every transition between the alaskite and the quartz; and the schist has been, so to speak, saturated with this siliceous material, which forms seams and thin lenses in it. The auriferous quartz-lenses in the mine in many places run laterally into quartz-feldspar rock (alaskite). As a rule, the values grow insignificant with the coming-in of the feldspar, but occasionally high values may still be found.

"The general conclusion is, that here a series of fissile shales and thin-bedded limestones has been invaded by a very siliceous granitic intrusion which has metamorphosed the sediments to schists. *The quartz has plainly the same origin and nature as the alaskite, both being siliceous phases of a granitic magma* [the italics are mine.—J. B. H.]. The gold in the quartz is usually free, sometimes associated with scattered galena [and pyrite.—J. B. H.]. Greenstone or diorite dikes cut the veins or follow along them, but are of later age. Along the dikes there has been water-circulation, resulting sometimes in impoverishment, sometimes in relative concentration of the original values.

"This zone of veins outcrops for a mile along the mountain side. At one point, some distance below the vein-zone, free gold in fresh alaskite-pegmatite country-rock was found.

"In the main, the other gold-mines or prospects of the district have exactly the same geological relations."

At my first examination of the Blair properties, in December, 1900, having, to guide me, the thorough reports of James D. Hague and George W. Maynard, I spent only one day on the hill; at my second visit, in May, 1905, I was half a day at the Blair mines and three days at the adjoining Valcalde group.

The mines are on ridges north from the Silver Peak, not on that mountain proper, which rises 1,500 ft. higher (to 9,000 ft.). It is volcanic; the various flows extend for miles easterly, and the successive stages of its growth are marked. It is reported that there is on the top an oblong depression, 2,000 ft. long, filled with water from melting snow.

Many mining engineers, who have examined veins in schists, will recognize the accuracy of Mr. Spurr's description of the formation in lenses, the disappearance both horizontally and vertically, and the replacement by overlapping ones. They also

have sampled veins in granite which have passed gradually from quartz to granite, and have noted the usual disappearance of metallic values with the appearance of the feldspars.

At my first visit, having no idea of the quartz ever being considered a phase of the granite, and at my last, being busily engaged with the economic features of the Valcalde group, I did not closely study the occurrence of alaskite within the granitic area; but it was seen in proximity to the great cuts on the Drinkwater mine, especially on the northeasterly or hanging-wall; and large masses in front of the vein presented a gneissoid appearance and were extremely silicified. In the southwesterly or foot-wall of the veins, the rock appeared to be normal granite, with muscovite and biotite; occasionally it looked as if the muscovite might be an alteration-product, but usually the rock was in normal condition, except that in all the pieces found the biotites were in the last stages of alteration. Alaskite was observed in other places among the mines, and away from the veins; and it seemed as if the absence of the micas was due, in part, to their elimination near the veins and other zones of movement, and sometimes to differentiation of the magma. The lenses in the schists are usually alaskite, but as most of these areas have been subjected to solfatarism, I could not decide whether the absence of the mica was primary or secondary. At the Drinkwater group the outer area bordering the limy shales is alaskite, and at the Valcalde group the granite adjoins the same rocks. The whole granitic mass of the mines is one magma. There has been fissuring of the normal granite, attended with injection of dikes and formation of veins, but sometimes without either. The micas adjacent to the movement have been more or less destroyed (as in the Boise basin) and aplite has been formed; and again aplite occurs as a phase of the original magma.

The whole granitic area is slightly fractured, the cracks cemented with the usual quartz as seen in granite, sometimes auriferous, usually not. These quartz seams are white and solid, glassy, chalcedonic or crystalline, and contain cavities, which are sometimes filled in with chalcedonic quartz.

Mr. Spurr speaks of finding gold in fresh alaskite-pegmatite country-rock below the veins. I found coarse gold at a point in the gulch below the Frank No. 2 mine, possibly on the Co-

lumbus, and south of the New York, from 200 to 500 ft. from the veins. The gulch follows a line of movement occupied more or less by a greenstone dike, from 6 to 8 in. wide, dipping flatly to the west. At this particular place the dike is not seen. Along the denuded foot-wall the alaskite is unaltered, except for small deposits of quartz and iron in masses an inch or so in diameter where the gold occurred, and which I take to have been connected with a small quartz vein 6 in. or less wide, intermittently accompanying the dike, which is also the foot-wall. This vein outcrops at the bottom of the gulch, and the quartz is clearly different from the component quartz of the alaskite. Its strike is NE. and dip NW.; the Blair veins strike NW. and dip NE.; and the Valcalde veins in this neighborhood strike north and dip east.

The following characteristics of the Blair veins were noted: Beginning at the workings farthest south, a 50-ft. tunnel is run in the foot-wall, and two cross-cuts made to the vein; the first one is 20 ft. in the solid white vein-quartz, and not through it; the quartz comes in on well-defined fissuring, course N. 30° W., with regular dip 20° NE. The second cross-cut just enters, at the roof, the same white quartz; there is strong fissuring on the contact; the course is more westerly and the dip is the same as in No. 1. The foot-wall is alaskite, containing a few quartz seams; the vein, as specified, is hard white quartz, separated from the foot-wall by uniform and distinct fissuring. The workings on the south side of the gulch expose the vein with the same quartz and the same flat dip, which follows a well-defined fissuring of the alaskite, and a thin greenstone dike, also fissured. A projected cross-section, showing the uniform dip of the Crowning Glory and Drinkwater veins for 1,000 ft. in depth, is given in Fig. 1.

The main Blair deposits, as Mr. Spurr says, occur in two separate veins; and it may be added that these are parallel and 100 ft. apart.

This outcrop of sheared country-rock and quartz, from 75 to 100 ft. wide, striking about N. 35° W., and dipping from 15° to 50° NE., can be traced for 6,000 ft. across a deep gulch, from the Crowning Glory to the New York. Throughout the whole distance, it is attended with fissuring. At the New York there is a belt of the limy shale, with possibly a fissured

dike which the vein follows, being always parallel to the fissuring. The quartz outcrop is very prominent for 500 ft. over the New York hill, and extends some distance beyond. The belt of foreign rock (limy shale, etc.), included in the granite, is about 100 ft. wide, but is local; another inclusion joins it on the north, more evidently the limy shale country-rock; here both the shale and granite are sheared, but more nearly north and south than at the vein, and with some silicification. Alongside the vein the granite is not sheared on the New York (as it is further south),—as if there had been enough of the shale to take up the movement.

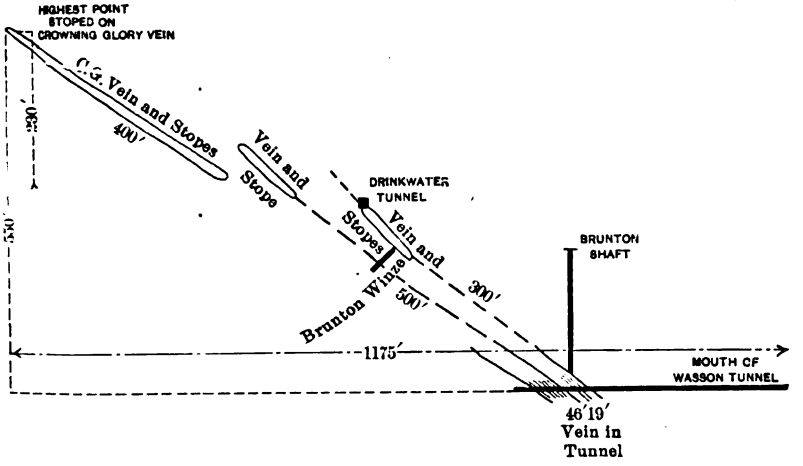

FIG. 1.—PROJECTED CROSS-SECTION OF CROWNING GLORY AND DRINKWATER VEINS.

There are, perhaps, three ages of greenstone dikes,—a diorite quite recent, running NW–SE.; a greenstone later than the veins and sometimes faulting them; and a greenstone older than the veins, which, to a great extent, the latter have followed.

Mr. Spurr thinks that all the dikes are later than the veins; but those followed by the veins sometimes inclose them, and the quartz is not sheared or broken, while the dike, especially that portion occupied by the vein, is sheared to schistosity. The quartz, both in the dikes and granite, is usually remarkably clean. Distinct silicification of the dikes is seen, which, however, might be secondary.

The Sentinel mine is on the divide between the New York and the Drinkwater, in the limy shale. The only ore-body and occurrence of quartz of consequence is at the open-cut alongside the road. This lens is about 30 ft. long, 20 ft. at the widest, strikes N. 20° W., and dips from 20° to 25° E., conformably with the schists. It is near the granite contact. The fissuring differs from that of the Blair mines, and agrees with the regular foliation of the limy shales; it continues down hill to the north, and is accentuated by lenticular streaks of alaskite intrusions. There has evidently been solfataric action along it, resulting in alteration on a small scale of the schists, and sometimes of the alaskite, and the formation of compact, crystalline and chalcedonic seams of quartz. On the whole, the silicification seems to have affected the schists more than the alaskite.

The Valcalde group, adjoining the Blair, exhibits much narrower veins. It comprises in one vein-system the Columbus, Lincoln, Frank No. 2, Washington, and Porto, to which might be added the Lucky Sam, owned by other parties. It seems as if all these claims were on one vein. At least, their characteristics are so uniform, and the portions developed occupy such relative positions, that they may be considered as belonging together. The vein-fissuring and deposition of quartz has followed a pre-existing flat dike, sometimes horizontal, and again dipping as much as 15° easterly or westerly; the dike as seen is from a few inches to 5 ft. thick, and the quartz from a few inches to 6 ft. The dike is distinctly sheared, as is also the granite near the contact, and, in some places, for a foot or two away, the quartz is not broken in the least. The quartz, which is sometimes lenticular in the sheared dike, also occurs in continuous streaks several feet wide within the dike, and also on top of it, with the granite for a distinct hanging-wall. In some places the dike is not seen at all, the quartz occurring as a regular streak in the granite, from 4 to 6 ft. wide, with a remarkably smooth and well-defined hanging-wall; the foot-wall is not exposed.

This flat fissure, extending from the New York 2,000 ft. southerly, outcrops along both sides of a north-and-south gulch (the central portion having been eroded away), and terminates, so far as known, in the basin at the head of it. Laterally, it may be 1,500 ft. wide; this width is only indicated by the Porto

mine. It has been disturbed by north-and-south movements, with and without dikes.

The area is either granite or alaskite, the latter in small patches. The quartz is entirely similar to that of the Blair mines, carrying a little galena and iron sulphides in the best ore.

The Soda mine lies south of the flat vein above described. The vein strikes north and dips 50° westerly. The hard, white vein-quartz is similar to that of the other mines, the best containing galena and pyrite. At the working farthest south it is found on the hanging-wall of a lenticular mass of an alaskite dike in limy shale. About 30 in. of the alaskite has been silicified. The east or hanging-wall of the quartz is limy shale and a greenstone dike, the relations of which could not be ascertained. The wall is fissured parallel to the vein. The foot-wall is alaskite; and the quartz merges into it. The alaskite lens, as developed, is 25 ft. long, 10 ft. wide at the middle, and of unknown extent, the northern half only being exposed. Beyond this northern half no more alaskite is found; but the vein, composed of quartz stringers and lenses parallel to the foliation of the schists, has been developed, with a width of from 6 to 10 ft., for 300 ft. further.

The Salisbury mine is in granite, a quarter of a mile from the end of the flat vein. It strikes N. 18° E. and dips 55° easterly. The foot-wall is well defined by 2 ft. of strong fissuring, with a small dike. The vein is 40 in. wide and merges into the granite, having no defined hanging-wall; but the width of the vein, developed for 55 ft., is uniform. It is cut off on the strike by a NW. fault and dike, dipping northeasterly, which carries quartz without values, as the result of a secondary silicification. The vein-quartz is, like that of the other mines, hard and white, and carrying galena and pyrite.

The Paris mine has about the same character as the Soda, but without an alaskite dike; the inclosing walls are schists, within a granite area; the veins are lenticular and small, from 2 to 4 ft. wide, and contain the same white quartz, with galena and pyrite in the best ore. The course is north and south, and the dip 35° east.

A few specimens from the Valcalde group exhibited: (1) wire gold in soft crystalline quartz (called "decomposed" by

the miners); (2) crystalline gold in a dog-tooth quartz lining of a cavity, which was afterwards filled with chalcedony; (3) sheets of gold from cracks in chalcedony; and (4) particles of gold in the ordinary vein-quartz, that has been freed by oxidation of the sulphides.

From the above it appears to me: (1) That this district presents bodies of quartz of uniform type, following a well-defined fracture-zone with regular course and dip, each great fissure having its own direction, varying from NW. in the Blair mines to N. 18° E. in the Salisbury mine, and a dip from horizontal to 15° westerly and 55° easterly, the easterly dip prevailing.

(2) That the values are in the quartz, which is confined to narrow lateral limits, being well-defined walls, which may be granite, schist, or, in a subsidiary way, greenstone dikes. The passing of the quartz into the granite occurs in the usual manner of veins in a granitoid rock; and the relative amount of accompanying silicified or mineralized granite is not more than usual.

(3) That, consequently, the veins are not siliceous segregations from the granite, but have been formed in the usual manner by ascending waters along lines of fracturing.

No. 24.

The Occurrence of Stibnite at Steamboat Springs, Nevada.

BY WALDEMAR LINDGREN, WASHINGTON, D. C.*

(Washington Meeting, May, 1905. *Trans.*, xxxvi., 27.)

THE important investigations of Dr. G. F. Becker at Steamboat Springs, Nev., in 1885, aided by the analytical work of W. H. Melville, established the fact that sulphides were being deposited at the surface by hot ascending waters.[1] Steamboat Springs is situated near the eastern base of the escarpment of the Sierra Nevada, six miles distant from the Comstock lode. In a region of former volcanic activity, hot springs with a temperature of about 80° C. break forth through a fissure in granodiorite, and at the base of a basaltic bluff the waters have deposited a large amount of siliceous and calcareous sinter, some of which is colored red by antimony sulphide. The sinter from one of the springs was analyzed by Mr. Melville,[2] and his results, re-calculated to grams per kilogram, showed:

	Grams per Kilogram.
Ferric oxide,	1.0263
Antimonious and arsenious sulphides,	22.9298
Mercuric sulphide,	0.0021
Cupric sulphide,	0.0124
Lead,	0.0211
Gold,	0.0010
Silver,	0.0003

The relative quantities of antimonious and arsenious sulphides are not given in the above analysis, but I believe that the former greatly predominated.

The water of one of the springs was also analyzed by Melville and the re-calculation of this analysis to salts that were possibly present is given in Table I.

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[1] *Monograph XIII., U. S. Geological Survey*, pp. 331–353.

[2] *Op. cit.*, p. 344 (Sample II.).

TABLE I.—*Possible Composition of the Water of Steamboat Springs, Prior to Oxidation.*[3]

	Grams per 10 Liters.
Ferrous carbonate, $FeCO_3$,	0.0029
Magnesium carbonate, $MgCO_3$,	0.0099
Calcic carbonate, $CaCO_3$,	0.1577
Calcic phosphate, $Ca_3P_2O_8$,	0.0137
Potassic chloride, KCl,	1.9735
Lithic sulphate, Li_2SO_4,	0.5650
Sodic chloride, NaCl,	14.1475
Sodic sulphydrate, NaHS,	0.0358
Sodic sulphate, Na_2SO_4,	1.1147
Sodic bicarbonate, $NaHCO_3$,	2.9023
Sodic monocarbonate, Na_2CO_3,	0.4314
Sodic biborate, $Na_2B_4O_7$,	3.1368
Sodic tetrasilicate, $Na_2Si_4O_9$,	3.9090
Sodic sulphantimonide, Na_2SbS_3,	0.0100
Sodic sulpharsenide, Na_2AsS_3,	0.0866
Alumina, Al_2O_3,	0.0025
Sodium-mercury sulphide, HgS, nNa_2S,	trace

The recalculation given in Table I. is, of course, only of very approximate value, since it is not known with certainty in what condition the different acids and bases are present. Moreover, the salts are partly dissociated. Attention should be called to the fact that the water contains far more arsenic than antimony, but during its filtration a red precipitate formed, consisting of arsenic and antimony sulphides,—in what relative amounts the report does not state.

Having assisted Dr. Becker in his examinations in 1885, I naturally felt a strong interest in this locality; and, in 1901, I revisited the place for a few hours, making a few observations which are here recorded.

The flow of water from the springs was found to be greatly reduced, probably on account of clogging of the channel. Several bore-holes had been sunk in order to obtain a better flow, and from these holes fragments of quartz had been brought up which were said to assay high in gold and silver. Of this I know nothing except from hearsay; but, at any rate, these results seem to have stimulated prospecting activity, for a shaft had recently been sunk to a depth of 30 ft. near the railway-station, on the sinter-flat a few hundred feet away from, and about 20

[3] *Op. cit.*, p. 347.

ft. above, Steamboat creek, which is the main drainage-line of the valley. After sinking 25 ft. through sinter, a loose sandy gravel was struck containing well-washed pebbles of granite and andesite, which carried so great an abundance of hot water as to lead to the suspension of mining operations. The gravel was said to contain small quantities of gold and silver, but I am not prepared to discuss this aspect of the case; moreover, the assays or the material would have no great value regarding the derivation of the gold and silver if found, for they might have been introduced in different ways. A sample of the same or similar material, transmitted to me in the summer of 1904 by Mr. W. H. Weed, was assayed and yielded a trace of gold.

Upon examining the dump, I found that the gravel throughout contained small shining prisms and particles of metallic luster. A generous sample of the material was collected, but further work was delayed, until 1903, when an examination of the sandy part of the gravel showed it to contain a considerable quantity of stibnite, in the form of loose slender prisms of the usual type, up to about 1mm. in length, and usually without terminal faces. The prisms are sometimes bent and often combined in radiating groups, and may be observed adhering to the surface of nearly every pebble of the gravel, both large and small. Some of the larger granite-cobbles, which usually are soft and decomposed, contain bunches of stibnite crystals in cracks and crevices. With the exception of clastic magnetite, the only other metallic mineral found in the gravel is pyrite, which forms loose or intergrown crystals of octahedral form, sometimes combined with the cube. In many cases both pyrite and stibnite have crystallized on the surface of pebbles, the former often being tarnished to a black color. Grains of quartz occur with the pyrite, but they are not clearly crystallized and may be clastic. A black opaline material containing about 1 per cent. of carbon, according to Dr. E. T. Allen, of the U. S. Geological Survey, sometimes adheres to the andesite pebbles.

In order to obtain an idea of quantitative relationships, the sandy part of the gravel was further examined by Dr. E. T. Allen, who found that lead, copper, zinc and mercury were absent, and that the material contained antimony, 0.4, arsenic, 0.067, and sulphur, 1.88 per cent., which corresponds to stib-

nite (Sb_2S_3), 0.56; orpiment, (As_2S_3), 0.107; and pyrite (FeS_2), 3.13 per cent.

It is not certain in what form the arsenic is present. Stibnite does not usually contain arsenic, and, on the other hand, no separate arsenical mineral could be recognized.

That stibnite and pyrite could be of clastic origin is entirely out of the question, and I believe it absolutely certain that they have been deposited by the hot waters which permeate the gravel. Considering that the waters have been shown to contain a considerable quantity of antimony, the occurrence seems of great interest.

No metallic sulphides, corresponding in appearance to the normal minerals, were found by Dr. Becker in the sinters, but cinnabar occurs disseminated in the decomposed granite, some distance away from the present springs. The antimonious sulphide, which colors parts of the sinter and always appears red and amorphous, was called metastibnite by Dr. Becker. The absence of ordinary minerals of metallic luster indicated, in a way, a missing link in the chain of evidence to prove the deposition of ores from hot ascending waters; and this link is now supplied by the observations recorded above.

Physical conditions differing very slightly from those at the actual surface will evidently produce crystallized minerals of normal habit and form. Many years ago Senarmont succeeded in forming crystals of stibnite from the amorphous sulphide by heating it to 250° C. in a closed tube with a solution of sodium carbonate.

During the investigation of the quicksilver-deposits of the Pacific slope, Messrs. Becker and Melville found that stibnite is easily crystallized from solutions similar to the waters of Steamboat Springs in sealed tubes heated to about 150° C. This renders it probable that a moderate pressure, such as exists at a small distance below the surface, is sufficient to induce the formation of the crystals described in this paper. Very likely, also, the presence of organic matter in the gravel is one of the conditions favoring such deposition.

Many important deposits of stibnite occur in sedimentary rocks in a manner which renders very probable a genesis somewhat similar to that of the occurrence here described.

No. 25.

A Summary of Lake Superior Geology with Special Reference to Recent Studies of the Iron-Bearing Series.*

BY C. K. LEITH, MADISON, WIS.

(Lake Superior Meeting, September, 1904. *Trans.*, xxxvi., 101.)

General Geology of the Lake Superior Iron-Bearing and Copper-Bearing Series.

* * * * * * * * * *

The ores of the region are contained in rocks of pre-Cambrian age, which, for most of the country up to recent years, have usually been referred to as "crystalline schists" or "crystalline complex;" and regarded principally as a metamorphosed basement-unit upon which the sedimentary rocks, beginning with the Paleozoic, were laid down. In the Lake Superior region this pre-Cambrian complex presents an unusual variety of rocks with determinable relations. It has been possible, with the large expenditures which the magnitude of the iron-mining industry warrants, to work out their stratigraphy to a larger degree than has been possible in almost any other area of pre-Cambrian rocks.

* * * * * * * * * *

[The portion here omitted contains descriptions of the Archean, Algonkian, and Keweenawan rocks of the several districts, their structure, distribution, correlation, and succession. Table I. and the geological map of the Lake Superior region belong to this portion, but are here reproduced on account of their value as guides to the readers of the rest of the paper.]

The simplest and clearest conception of the pre-Cambrian succession for the Lake Superior region may perhaps be obtained by thinking of it as primarily divided into six series—Keweenawan, Upper Huronian, Middle Huronian, Lower Huronian, Keewatin, and Laurentian—all but the last two separated by unconformities of varying and disputed relative im-

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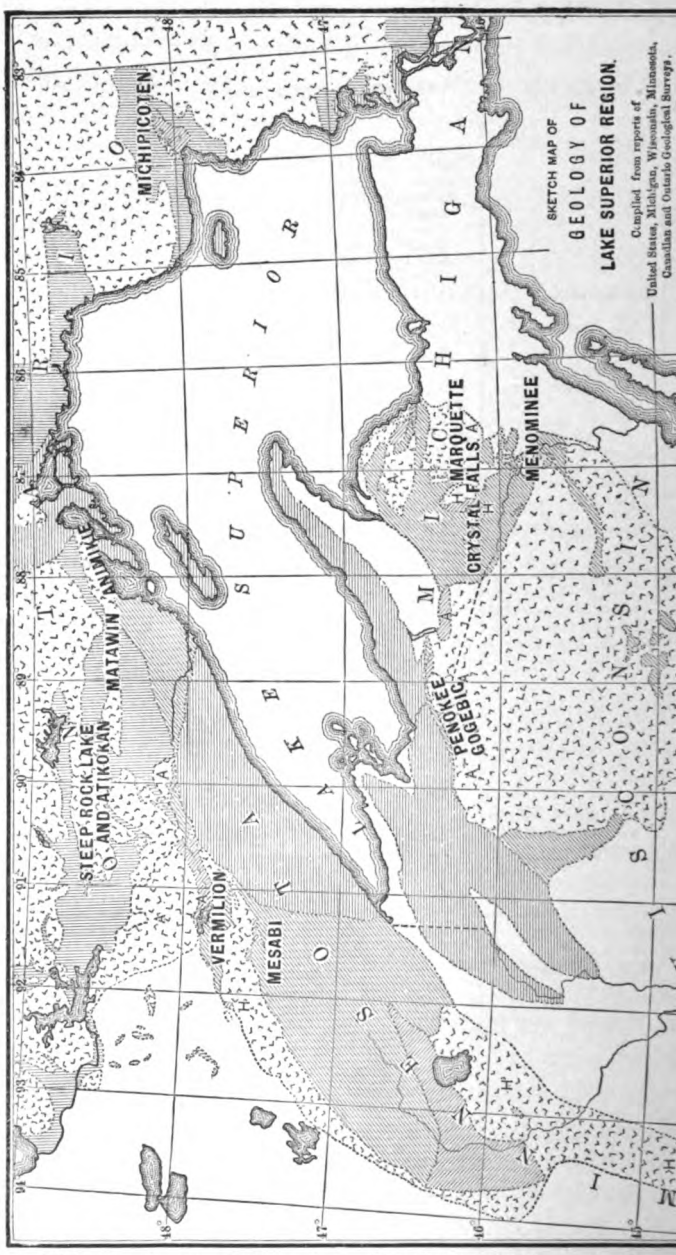
TABLE I.—*Correlation of Pre-Cam*

		Mesabi District.	Penokee-Gogebic District.	Vermilion District.	Marqu Distri
ALGONKIAN.	KEWEENAWAN. (Copper-bearing.)	Great basal gabbro and granite.	Gabbros, diabases, etc.	Great gabbro.	
	UPPER HURONIAN. (Iron-bearing.)	*Mesabi Series:* Virginia formation (upper slate). Biwabik formation (iron-bearing and productive). Pokegama formation (quartzite and quartz-slate).	*Penokee-Gogebic Series:* Tyler formation (upper slate). Ironwood formation (iron-bearing and productive). Palms formation (quartz-slate).	*Animikie Series:* Upper slate formation. Gunflint formation (iron-bearing, but non-productive).	*Upper Marq* Michiga forma (slate) ly rep by C burg canic f tion). tains pr tive iro near ba Ishpemin mation sisting mem Bijiki (in we part of trict an Good quart contai produc detrital at its ba
	MIDDLE HURONIAN. (Iron-bearing.)				*Middle Marq* Negaunee mation bearing producti Siamo sla Ajibik qu ite.
	LOWER HURONIAN.	Granite intrusive in lower formations. Slate-graywacke-conglomerate formation.	Bad River limestone formation (cherty limestone). Quartzite.	Intrusives. Knife slate. Agawa formation (iron-bearing, but non-productive). Ogishke conglomerate.	*Lower Marq* Wewe sla Kona dolo Mesnard quart
	LAURENTIAN. (Intrusive into Keewatin.)	Granites and porphyries.	Granite and granitoid gneiss.	Intrusive granites, porphyries and greenstones.	Granite, nite. Palmer gnei
ARCHEAN OR BASEMENT COMPLEX.	KEEWATIN. (Iron-bearing.)	Greenstones, hornblende-schists and porphyries.	Green schists and fine-grained gneiss.	Soudan formation (iron-bearing and productive). Ely greenstone, an ellipsoidally-parted basic igneous and largely volcanic rock.	Kitchi sc and M schist, the ter band and in a places taining row bands non-prod tive iro bearing f mation. Peridotite.

Series of the Lake Superior Region.

Crystal Falls District.	Menominee District.	Keweenaw Point.	Michipicoten.	Other Parts of Ontario North of Lake Superior.
		Lower, Middle and Upper Keweenawan. Interbedded lavas and sediments grading up into sandstones.		Interbedded sediments and traps along Lake Superior shore.
Michigamme formation, containing a productive iron-bearing horizon not separated in mapping for much of the district.	*Upper Menominee:* Hanbury formation, mainly slate, bearing in lower portions calcareous slates, etc., containing siderite and iron oxide. Vulcan formation, consisting of three members: Curry member (iron-bearing), Brier slate and Traders member (iron-bearing).			Animikie series of northwest shore comprising iron-formation overlain by slate.
Hemlock formation (basic volcanic). Negaunee formation (iron-bearing).	Negaunee formation doubtfully present.			Undivided pre-Animikie sediments, mainly graywackes, slates and conglomerates, much metamorphosed.
Randville dolomite. Sturgeon quartzite.	*Lower Menominee:* Randville dolomite. Sturgeon quartzite.		Basic eruptives. Acid eruptives. Doré conglomerate.	
Granite.	Granites and gneisses.		Granites and gneisses.	Granites and gneisses.
	Quinnesec schist. (?)		Eleanor slates. Helen formation (iron-bearing and productive). Wawa tuffs. Gros Cap greenstones.	Greenstone and Iron formation, similar to that of Vermilion district of Minnesota.



This sketch-map of the geology of the Lake Superior region is ge
modified from a general geological map of the Lake Superior regio
of ten inches to the mile, compiled by C. R. Van Hise and C. K. Le
cation in a final general monograph on Lake Superior geology in p
the U. S. Geological Survey.

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The Iron-Ores.

Nature, Occurrence, Relations to Adjacent Rocks, Origin.

A general summary of the work of the U. S. Geological Survey on the iron-ores of the Lake Superior region is given by Van Hise.[11] The present summary covers much of the same ground, but includes also developments subsequent to the publication of his report.

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The iron-formations of the different districts and ages are surprisingly similar in their general characters. Indeed, it was long assumed, erroneously, that because of their similarity they must be of the same age and origin. A single description will therefore suffice for them all.

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It may be emphasized that almost the entire bulk of the iron-formation now consists of iron oxide and silica, with carbonates and alumina present in subordinate quantity. The varying combination of part or all of these constituents, mechanically, or chemically, or both, gives all of the rock-types above listed.

A series of cross-sections, Figs. 1, 2, 3 and 4, summarizes better than a description the structural relations of the ores to the adjacent rocks in the different districts and formations.

It has been shown that the ferruginous cherts, jaspers, amphibole-magnetite schists, and iron-ores of the iron-formation

result from the alteration either of the cherty iron carbonate or of ferrous silicate (greenalite), or, to a minute extent, from iron sulphide. The small amounts of iron carbonate or ferrous silicate now found in the formations represent mere remnants left

FIG. 1.—GENERALIZED VERTICAL SECTION IN MARQUETTE DISTRICT, MICHIGAN, SHOWING RELATION OF DIFFERENT CLASSES OF ORE-DEPOSITS TO ASSOCIATED FORMATIONS.

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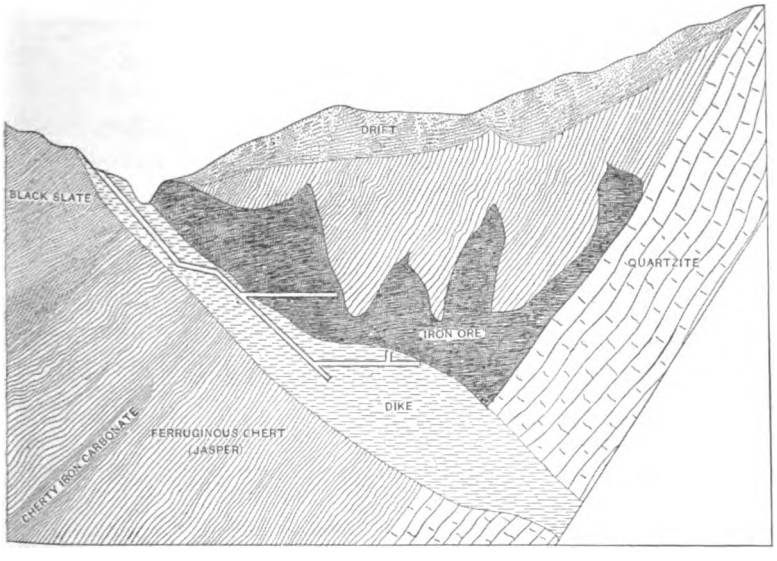

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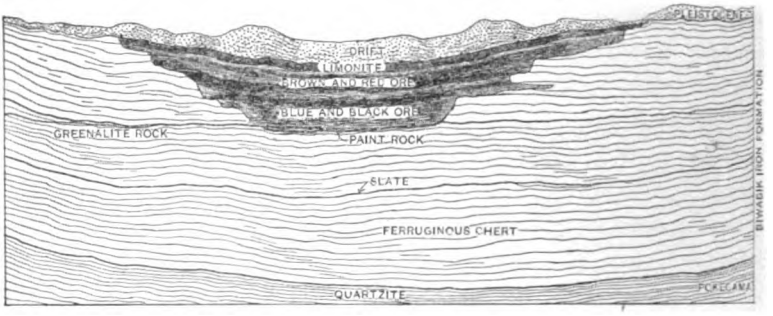

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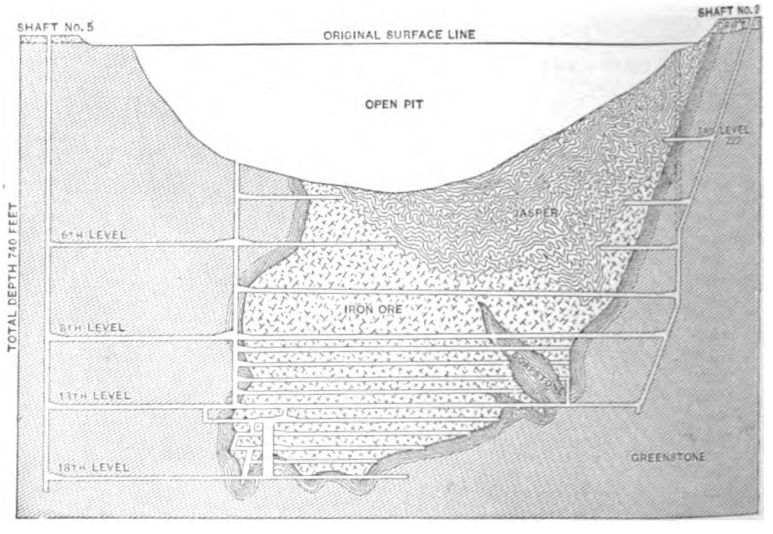

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ores and jaspers, often of the largest deposits, develop side by side contemporaneously from the alteration of iron carbonates or iron silicates.

The agent of the alteration is water, coming more or less directly from the surface, carrying oxygen and carbon dioxide. The concentration of the ores has been found to occur where such waters have been converged. Various factors have determined this convergence—fracturing and brecciation of the iron-formation, existence of impervious layers in such attitudes as either to converge waters coming from above or to impound the waters and deflect their course between two layers. The presence of an impervious layer, forming a pitching-trough, is perhaps the most conspicuous structural feature determining the convergence of waters concentrating the ores. The impervious troughs consist, in the Mesabi district, of slate or paint-rock layers within the formation itself; in the Vermilion district, of greenstone with which the iron-formation is infolded or interbedded; in the Penokee-Gogebic district, of the intersection of diorite dikes with a foot-wall quartzite; in the Marquette district, of a greenstone intrusive into the iron-formation, or of a slate underlying the iron-formation; in the Menominee district, of dolomite underlying the iron-formation or of slate layers within the formation itself. In all these districts, except the Mesabi, the presence of this impervious basement seems to be clearly the controlling factor in the convergence of waters which have concentrated the ores.

In the Mesabi district, also, impervious troughs may be important, but they probably are subordinate to, or, at least, not more important than, other factors. The iron-formation and its associated rocks lie in beds on the south slope of the Giant's range, and dip off gently to the south at angles averaging from 8° to 10°. In addition to the general southward tilting of the beds, they are gently flexed into folds with axes transverse to the trend of the range. Waters falling on the south slope of the Giant's range, and flowing to the south, enter the eroded edges of the iron-formation and continue their way down along its layers, some of which are pervious and some of which are slaty and comparatively impervious to water. The flow thus tends to become concentrated along the axes of the synclines which pitch gently to the southward. Such synclines are not necessarily surface-troughs. They are evidenced by the attitude of the layers of the iron-formation, and may not be apparent in the unequally-eroded rock-surface or at the surface

TABLE I.—*Possible Composition of the Water of Steamboat Springs, Prior to Oxidation.*[3]

	Grams per 10 Liters.
Ferrous carbonate, $FeCO_3$,	0.0029
Magnesium carbonate, $MgCO_3$,	0.0099
Calcic carbonate, $CaCO_3$,	0.1577
Calcic phosphate, $Ca_3P_2O_8$,	0.0137
Potassic chloride, KCl,	1.9735
Lithic sulphate, Li_2SO_4,	0.5650
Sodic chloride, NaCl,	14.1475
Sodic sulphydrate, NaHS,	0.0358
Sodic sulphate, Na_2SO_4,	1.1147
Sodic bicarbonate, $NaHCO_3$,	2.9023
Sodic monocarbonate, Na_2CO_3,	0.4314
Sodic biborate, $Na_2B_4O_7$,	3.1368
Sodic tetrasilicate, $Na_2Si_4O_9$,	3.9090
Sodic sulphantimonide, Na_2SbS_3,	0.0100
Sodic sulpharsenide, Na_2AsS_3,	0.0866
Alumina, Al_2O_3,	0.0025
Sodium-mercury sulphide, HgS, nNa_2S,	trace

The recalculation given in Table I. is, of course, only of very approximate value, since it is not known with certainty in what condition the different acids and bases are present. Moreover, the salts are partly dissociated. Attention should be called to the fact that the water contains far more arsenic than antimony, but during its filtration a red precipitate formed, consisting of arsenic and antimony sulphides,—in what relative amounts the report does not state.

Having assisted Dr. Becker in his examinations in 1885, I naturally felt a strong interest in this locality; and, in 1901, I revisited the place for a few hours, making a few observations which are here recorded.

The flow of water from the springs was found to be greatly reduced, probably on account of clogging of the channel. Several bore-holes had been sunk in order to obtain a better flow, and from these holes fragments of quartz had been brought up which were said to assay high in gold and silver. Of this I know nothing except from hearsay; but, at any rate, these results seem to have stimulated prospecting activity, for a shaft had recently been sunk to a depth of 30 ft. near the railway-station, on the sinter-flat a few hundred feet away from, and about 20

[3] *Op. cit.*, p. 347.

ft. above, Steamboat creek, which is the main drainage-line of the valley. After sinking 25 ft. through sinter, a loose sandy gravel was struck containing well-washed pebbles of granite and andesite, which carried so great an abundance of hot water as to lead to the suspension of mining operations. The gravel was said to contain small quantities of gold and silver, but I am not prepared to discuss this aspect of the case; moreover, the assays or the material would have no great value regarding the derivation of the gold and silver if found, for they might have been introduced in different ways. A sample of the same or similar material, transmitted to me in the summer of 1904 by Mr. W. H. Weed, was assayed and yielded a trace of gold.

Upon examining the dump, I found that the gravel throughout contained small shining prisms and particles of metallic luster. A generous sample of the material was collected, but further work was delayed, until 1903, when an examination of the sandy part of the gravel showed it to contain a considerable quantity of stibnite, in the form of loose slender prisms of the usual type, up to about 1mm. in length, and usually without terminal faces. The prisms are sometimes bent and often combined in radiating groups, and may be observed adhering to the surface of nearly every pebble of the gravel, both large and small. Some of the larger granite-cobbles, which usually are soft and decomposed, contain bunches of stibnite crystals in cracks and crevices. With the exception of clastic magnetite, the only other metallic mineral found in the gravel is pyrite, which forms loose or intergrown crystals of octahedral form, sometimes combined with the cube. In many cases both pyrite and stibnite have crystallized on the surface of pebbles, the former often being tarnished to a black color. Grains of quartz occur with the pyrite, but they are not clearly crystallized and may be clastic. A black opaline material containing about 1 per cent. of carbon, according to Dr. E. T. Allen, of the U. S. Geological Survey, sometimes adheres to the andesite pebbles.

In order to obtain an idea of quantitative relationships, the sandy part of the gravel was further examined by Dr. E. T. Allen, who found that lead, copper, zinc and mercury were absent, and that the material contained antimony, 0.4, arsenic, 0.067, and sulphur, 1.88 per cent., which corresponds to stib-

nite (Sb_2S_3), 0.56; orpiment, (As_2S_3), 0.107; and pyrite (FeS_2), 3.13 per cent.

It is not certain in what form the arsenic is present. Stibnite does not usually contain arsenic, and, on the other hand, no separate arsenical mineral could be recognized.

That stibnite and pyrite could be of clastic origin is entirely out of the question, and I believe it absolutely certain that they have been deposited by the hot waters which permeate the gravel. Considering that the waters have been shown to contain a considerable quantity of antimony, the occurrence seems of great interest.

No metallic sulphides, corresponding in appearance to the normal minerals, were found by Dr. Becker in the sinters, but cinnabar occurs disseminated in the decomposed granite, some distance away from the present springs. The antimonious sulphide, which colors parts of the sinter and always appears red and amorphous, was called metastibnite by Dr. Becker. The absence of ordinary minerals of metallic luster indicated, in a way, a missing link in the chain of evidence to prove the deposition of ores from hot ascending waters; and this link is now supplied by the observations recorded above.

Physical conditions differing very slightly from those at the actual surface will evidently produce crystallized minerals of normal habit and form. Many years ago Senarmont succeeded in forming crystals of stibnite from the amorphous sulphide by heating it to 250° C. in a closed tube with a solution of sodium carbonate.

During the investigation of the quicksilver-deposits of the Pacific slope, Messrs. Becker and Melville found that stibnite is easily crystallized from solutions similar to the waters of Steamboat Springs in sealed tubes heated to about 150° C. This renders it probable that a moderate pressure, such as exists at a small distance below the surface, is sufficient to induce the formation of the crystals described in this paper. Very likely, also, the presence of organic matter in the gravel is one of the conditions favoring such deposition.

Many important deposits of stibnite occur in sedimentary rocks in a manner which renders very probable a genesis somewhat similar to that of the occurrence here described.

No. 25.

A Summary of Lake Superior Geology with Special Reference to Recent Studies of the Iron-Bearing Series.*

BY C. K. LEITH, MADISON, WIS.

(Lake Superior Meeting, September, 1904. *Trans.*, xxxvi., 101.)

General Geology of the Lake Superior Iron-Bearing and Copper-Bearing Series.

* * * * * * * * * *

The ores of the region are contained in rocks of pre-Cambrian age, which, for most of the country up to recent years, have usually been referred to as "crystalline schists" or "crystalline complex;" and regarded principally as a metamorphosed basement-unit upon which the sedimentary rocks, beginning with the Paleozoic, were laid down. In the Lake Superior region this pre-Cambrian complex presents an unusual variety of rocks with determinable relations. It has been possible, with the large expenditures which the magnitude of the iron-mining industry warrants, to work out their stratigraphy to a larger degree than has been possible in almost any other area of pre-Cambrian rocks.

* * * * * * * * * *

[The portion here omitted contains descriptions of the Archean, Algonkian, and Keweenawan rocks of the several districts, their structure, distribution, correlation, and succession. Table I. and the geological map of the Lake Superior region belong to this portion, but are here reproduced on account of their value as guides to the readers of the rest of the paper.]

The simplest and clearest conception of the pre-Cambrian succession for the Lake Superior region may perhaps be obtained by thinking of it as primarily divided into six series—Keweenawan, Upper Huronian, Middle Huronian, Lower Huronian, Keewatin, and Laurentian—all but the last two separated by unconformities of varying and disputed relative im-

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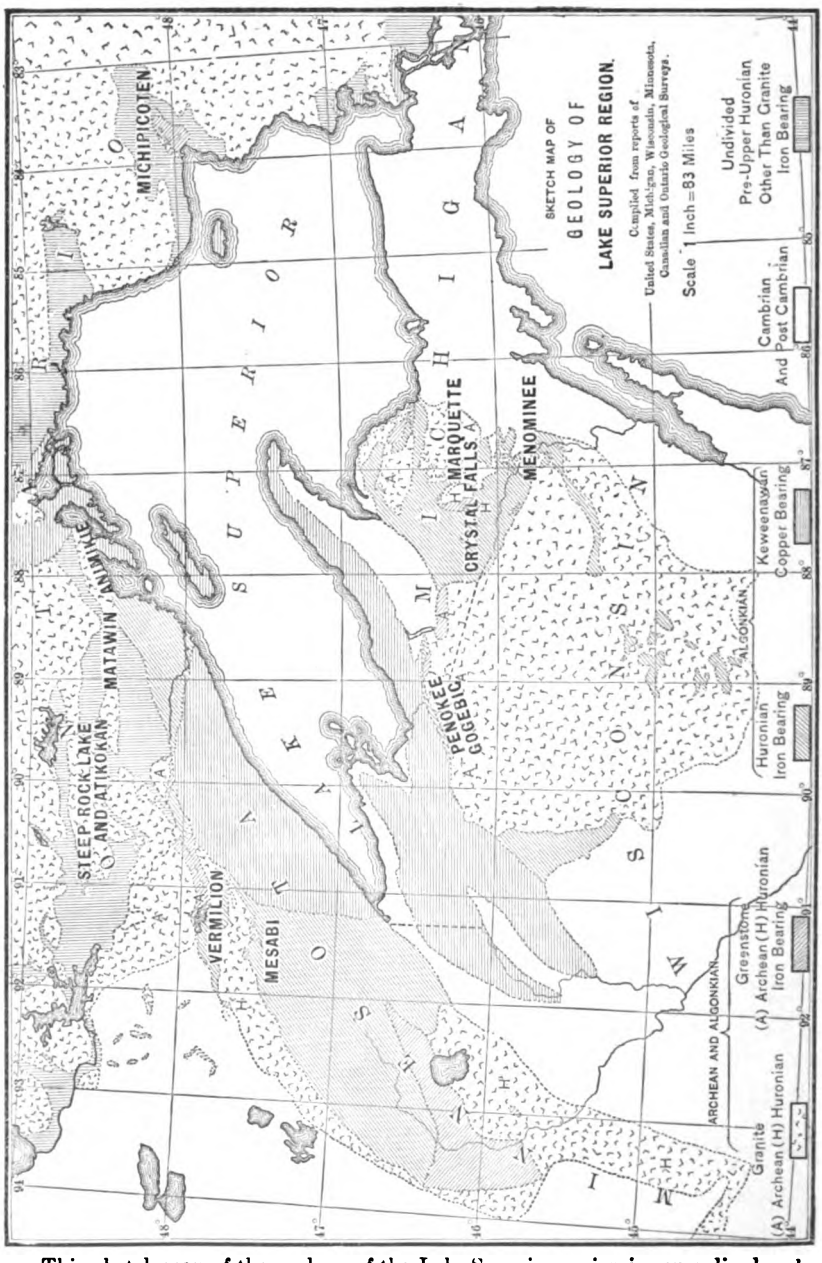
TABLE I.—*Correlation of Pre-Cambrian*

		Mesabi District.	Penokee-Gogebic District.	Vermilion District.	Marquette District.
ALGONKIAN.	KEWEENAWAN. (Copper-bearing.)	Great basal gabbro and granite.	Gabbros, diabases, etc.	Great gabbro.	
	UPPER HURONIAN. (Iron-bearing.)	*Mesabi Series:* Virginia formation (upper slate). Biwabik formation (iron-bearing and productive). Pokegama formation (quartzite and quartz-slate).	*Penokee-Gogebic Series:* Tyler formation (upper slate). Ironwood formation (iron-bearing and productive). Palms formation (quartz-slate).	*Animikie Series:* Upper slate formation. Gunflint formation (iron-bearing, but non-productive).	*Upper Marquette:* Michigamme formation (slate) (locally replaced by Clarksburg volcanic formation). Contains productive iron-ores near base. Ishpeming formation, consisting of two members: Bijiki schist (in western part of district) and the Goodrich quartzite containing productive detrital ores at its base.
	MIDDLE HURONIAN. (Iron-bearing.)				*Middle Marquette:* Negaunee formation (iron-bearing and productive). Siamo slate. Ajibik quartzite.
	LOWER HURONIAN.	Granite intrusive in lower formations. Slate-graywacke-conglomerate formation.	Bad River limestone formation (cherty limestone). Quartzite.	Intrusives. Knife slate. Agawa formation (iron-bearing, but non-productive). Ogishke conglomerate.	*Lower Marquette:* Wewe slate. Kona dolomite. Mesnard quartzite.
ARCHEAN or BASEMENT COMPLEX.	LAURENTIAN. (Intrusive into Keewatin.)	Granites and porphyries.	Granite and granitoid gneiss.	Intrusive granites, porphyries and greenstones.	Granite, syenite. Palmer gneiss.
	KEEWATIN. (Iron-bearing.)	Greenstones, hornblende-schists and porphyries.	Green schists and fine-grained gneiss.	Soudan formation (iron-bearing and productive). Ely greenstone, an ellipsoidally-parted basic igneous and largely volcanic rock.	Kitchi schist and Mona schist, the latter banded, and in a few places containing narrow bands of non-productive iron-bearing formation. Peridotite.

Series of the Lake Superior Region.

Crystal Falls District.	Menominee District.	Keweenaw Point.	Michipicoten.	Other Parts of Ontario North of Lake Superior.
		Lower, Middle and Upper Keweenawan. Interbedded lavas and sediments grading up into sandstones.		Interbedded sediments and traps along Lake Superior shore.
Michigamme formation, containing a productive iron-bearing horizon not separated in mapping for much of the district.	*Upper Menominee:* Hanbury formation, mainly slate, bearing in lower portions calcareous slates, etc., containing siderite and iron oxide. Vulcan formation, consisting of three members: Curry member (iron-bearing), Brier slate and Traders member (iron-bearing).			Animikie series of northwest shore comprising iron-formation overlain by slate.
Hemlock formation (basic volcanic). Negaunee formation (iron-bearing).	Negaunee formation doubtfully present.			Undivided pre-Animikie sediments, mainly graywackes, slates and conglomerates, much metamorphosed.
Randville dolomite. Sturgeon quartzite.	*Lower Menominee:* Randville dolomite. Sturgeon quartzite.		Basic eruptives. Acid eruptives. Doré conglomerate.	
Granite.	Granites and gneisses.		Granites and gneisses.	Granites and gneisses.
	Quinnesec schist. (?)		Eleanor slates. Helen formation (iron-bearing and productive). Wawa tuffs. Gros Cap greenstones.	Greenstone and Iron formation, similar to that of Vermilion district of Minnesota.



This sketch-map of the geology of the Lake Superior region is generalized and modified from a general geological map of the Lake Superior region, on a scale of ten inches to the mile, compiled by C. R. Van Hise and C. K. Leith for publication in a final general monograph on Lake Superior geology in preparation for the U. S. Geological Survey.

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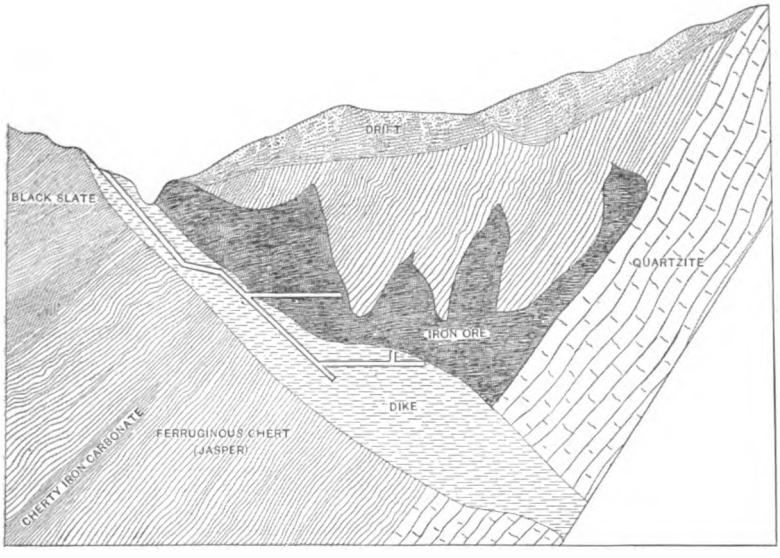

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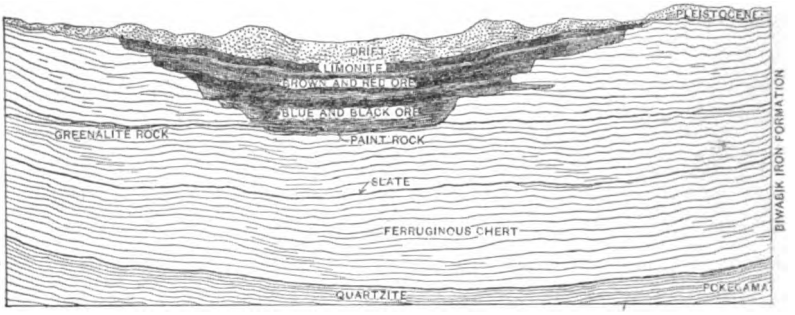

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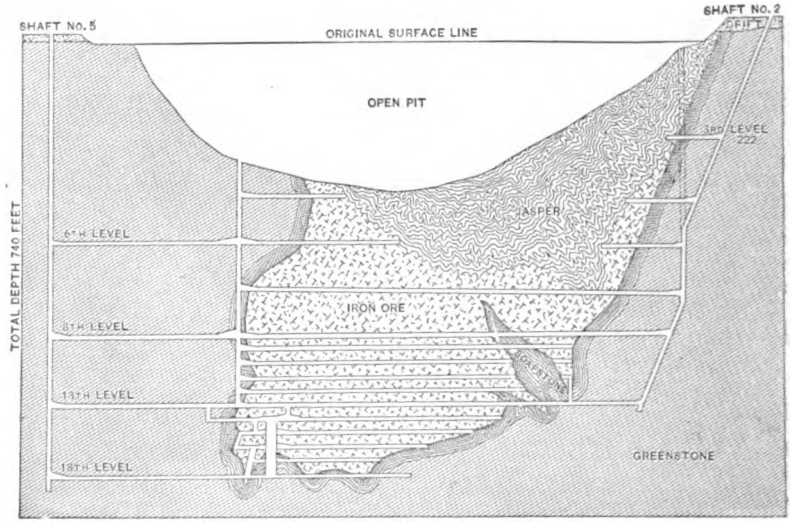

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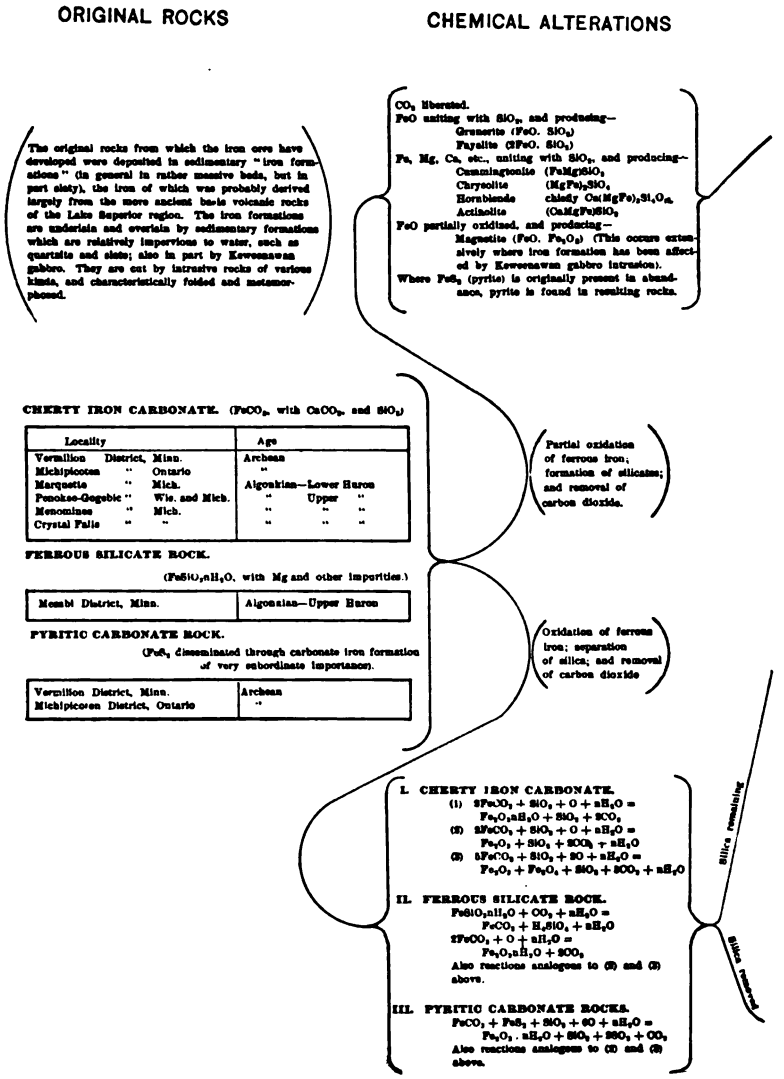
ores and jaspers, often of the largest deposits, develop side by side contemporaneously from the alteration of iron carbonates or iron silicates.

The agent of the alteration is water, coming more or less directly from the surface, carrying oxygen and carbon dioxide. The concentration of the ores has been found to occur where such waters have been converged. Various factors have determined this convergence—fracturing and brecciation of the iron-formation, existence of impervious layers in such attitudes as either to converge waters coming from above or to impound the waters and deflect their course between two layers. The presence of an impervious layer, forming a pitching-trough, is perhaps the most conspicuous structural feature determining the convergence of waters concentrating the ores. The impervious troughs consist, in the Mesabi district, of slate or paint-rock layers within the formation itself; in the Vermilion district, of greenstone with which the iron-formation is infolded or interbedded; in the Penokee-Gogebic district, of the intersection of diorite dikes with a foot-wall quartzite; in the Marquette district, of a greenstone intrusive into the iron-formation, or of a slate underlying the iron-formation; in the Menominee district, of dolomite underlying the iron-formation or of slate layers within the formation itself. In all these districts, except the Mesabi, the presence of this impervious basement seems to be clearly the controlling factor in the convergence of waters which have concentrated the ores.

In the Mesabi district, also, impervious troughs may be important, but they probably are subordinate to, or, at least, not more important than, other factors. The iron-formation and its associated rocks lie in beds on the south slope of the Giant's range, and dip off gently to the south at angles averaging from 8° to 10°. In addition to the general southward tilting of the beds, they are gently flexed into folds with axes transverse to the trend of the range. Waters falling on the south slope of the Giant's range, and flowing to the south, enter the eroded edges of the iron-formation and continue their way down along its layers, some of which are pervious and some of which are slaty and comparatively impervious to water. The flow thus tends to become concentrated along the axes of the synclines which pitch gently to the southward. Such synclines are not necessarily surface-troughs. They are evidenced by the attitude of the layers of the iron-formation, and may not be apparent in the unequally-eroded rock-surface or at the surface

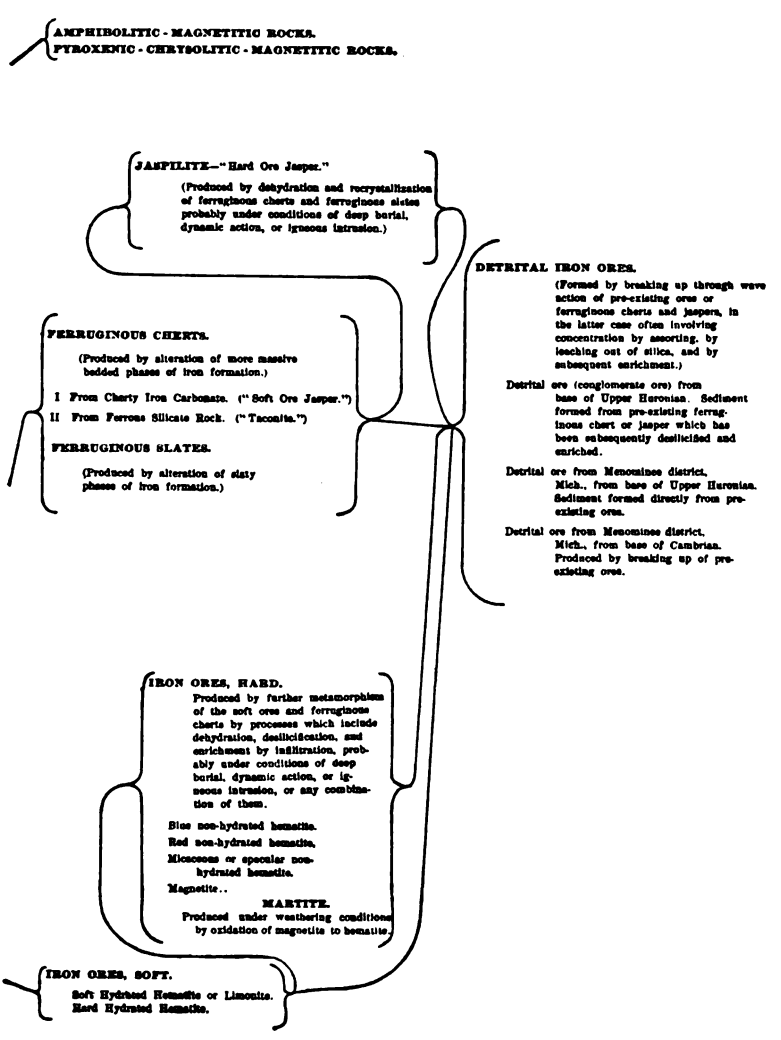
TABLE II.—*Origin and Development of the*

(Prepared for the St. Louis Exposition by C. R.


ORIGINAL ROCKS
CHEMICAL ALTERATIONS
The original rocks from which the iron ores have developed were deposited in sedimentary "iron formations" (in general in rather massive beds, but in part slaty), the iron of which was probably derived largely from the more ancient basic volcanic rocks of the Lake Superior region. The iron formations are underlain and overlain by sedimentary formations which are relatively impervious to water, such as quartzite and slate; also in part by Keweenawan gabbro. They are cut by intrusive rocks of various kinds, and characteristically folded and metamorphosed.
CO_2 liberated.
FeO uniting with SiO_2, and producing—
Grunerite (FeO. SiO_2)
Fayalite (2FeO. SiO_2)
Fe, Mg, Ca, etc., uniting with SiO_2, and producing—
Cummingtonite (FeMg)SiO_3
Chrysolite (Mg,Fe)$_2SiO_4$
Hornblende chiefly $Ca(MgFe)_3Si_4O_{12}$
Actinolite $(CaMgFe)SiO_3$
FeO partially oxidized, and producing—
Magnetite (FeO. Fe_2O_3) (This occurs extensively where iron formation has been affected by Keweenawan gabbro intrusion).
Where FeS_2 (pyrite) is originally present in abundance, pyrite is found in resulting rocks.
CHERTY IRON CARBONATE. ($FeCO_3$, with $CaCO_3$, and SiO_2)
Locality | Age
Vermilion District, Minn. | Archean
Michipicoten " Ontario | "
Marquette " Mich. | Algonkian—Lower Huron
Penokee-Gogebic " Wis. and Mich. | " Upper "
Menominee " Mich. | " "
Crystal Falls " " | " "
Partial oxidation of ferrous iron; formation of silicates; and removal of carbon dioxide.
FERROUS SILICATE ROCK.
($FeSiO_3nH_2O$, with Mg and other impurities.)
Mesabi District, Minn. | Algonkian—Upper Huron
PYRITIC CARBONATE ROCK.
(FeS_2 disseminated through carbonate iron formation of very subordinate importance).
Vermilion District, Minn. | Archean
Michipicoten District, Ontario | "
Oxidation of ferrous iron; separation of silica; and removal of carbon dioxide
I. CHERTY IRON CARBONATE.
(1) $2FeCO_3 + SiO_2 + O + nH_2O = Fe_2O_3.nH_2O + SiO_2 + 2CO_2$
(2) $2FeCO_3 + SiO_2 + O + nH_2O = Fe_2O_3 + SiO_2 + 2CO_2 + nH_2O$
(3) $4FeCO_3 + SiO_2 + 2O + nH_2O = Fe_2O_3 + Fe_3O_4 + SiO_2 + 4CO_2 + nH_2O$
II. FERROUS SILICATE ROCK.
$FeSiO_3nH_2O + CO_2 + nH_2O = FeCO_3 + H_4SiO_4 + nH_2O$
$2FeCO_3 + O + nH_2O = Fe_2O_3nH_2O + 2CO_2$
Also reactions analogous to (2) and (3) above.
III. PYRITIC CARBONATE ROCKS.
$FeCO_3 + FeS_2 + SiO_2 + 6O + nH_2O = Fe_2O_3 . nH_2O + SiO_2 + 2SO_2 + CO_2$
Also reactions analogous to (2) and (3) above.
Silica remaining
Silica removed

Iron-Ores of the Lake Superior Region.

Van Hise, C. K. Leith and W. N. Smith.)


RESULTING PRODUCTS
AMPHIBOLITIC - MAGNETITIC ROCKS.
PYROXENIC - CHERTOLITIC - MAGNETITIC ROCKS.
JASPILITE—"Hard Ore Jasper."
(Produced by dehydration and recrystallization of ferruginous cherts and ferruginous slates probably under conditions of deep burial, dynamic action, or igneous intrusion.)
FERRUGINOUS CHERTS.
(Produced by alteration of more massive bedded phases of iron formation.)
I From Cherty Iron Carbonate. ("Soft Ore Jasper.")
II From Ferrous Silicate Rock. ("Taconite.")
FERRUGINOUS SLATES.
(Produced by alteration of slaty phases of iron formation.)
DETRITAL IRON ORES.
(Formed by breaking up through wave action of pre-existing ores or ferruginous cherts and jaspers, in the latter case often involving concentration by assorting, by leaching out of silica, and by subsequent enrichment.)
Detrital ore (conglomerate ore) from base of Upper Huronian. Sediment formed from pre-existing ferruginous chert or jasper which has been subsequently desilicified and enriched.
Detrital ore from Menominee district, Mich., from base of Upper Huronian. Sediment formed directly from pre-existing ores.
Detrital ore from Menominee district, Mich., from base of Cambrian. Produced by breaking up of pre-existing ores.
IRON ORES, HARD.
Produced by further metamorphism of the soft ores and ferruginous cherts by processes which include dehydration, desilicification, and enrichment by infiltration, probably under conditions of deep burial, dynamic action, or igneous intrusion, or any combination of them.
Blue non-hydrated hematite.
Red non-hydrated hematite.
Micaceous or specular non-hydrated hematite.
Magnetite..
MARTITE.
Produced under weathering conditions by oxidation of magnetite to hematite.
IRON ORES, SOFT.
Soft Hydrated Hematite or Limonite.
Hard Hydrated Hematite.

of the irregular covering of glacial drift. The concentration of the flow along the synclines in the layers of the iron-formation seems so simple and evident that there is a temptation to generalize and say that the underground circulation has probably concentrated the ores along these broad synclines. When the district was first examined by the U. S. Geological Survey this simple explanation was applied. But further study shows that other factors modify the circulation of water and the localization of the ore, and that these secondary factors may be locally dominant.

The most important of these modifying factors is the fracturing of the iron-formation, which has furnished numerous trunk-channels for the circulation of underground-waters. The water has been confined to narrow, irregular and most devious trunk-channels formed by the fracturing of the iron-formation, and, while it has probably followed the fracture-openings along synclines to a greater extent than along anticlines, it has not filled the entire syncline formed by the folding of the iron-formation. The result is that the ores have developed along limited and irregular areas within the synclines. They may occupy a considerable part of the syncline, in which case the synclinal structure of the iron-formation may be observed in the layers of wall-rock adjacent to the ores. In other cases, they occupy so small a proportion of the syncline that the layers of the iron-formation in the adjacent wall-rock give no indication of synclinal dips. Not infrequently, several more or less independent deposits may have developed in the same general syncline, as, for instance, in the area adjacent to the town of Virginia. To put it briefly, the ores show such position, irregularity, extent, and relations to wall-rocks as to make applicable the expression sometimes heard in the district that the ores have developed through the "rotting" of the iron-formation along fractures, usually, but not always, in broad synclinal areas.

Other factors modifying the general underground-flow of water in the Mesabi iron-formation are the numerous impervious slaty layers within the iron-formation, and the Virginia slate capping the iron-formation of the south; all of which have considerable effect. So far as the water is free to flow southward through the iron-formation, the impervious layers serve

only to limit the flow below. But the continuous south dip of the impervious strata carries the waters down to a point when the ground is saturated and the waters are ponded between impervious layers above and below. That ponding actually occurs is shown by the fact that drill-holes penetrating the slates and entering the iron-formation frequently meet water under pressure, indicating artesian conditions. When ponded, the water seeks the lowest point of escape, which is likely to be found near the north margin of the slate-layers. The movement of the water towards the lowest point of escape causes a considerable lateral movement in the circulation, and this lateral movement has probably, at least in part, controlled the shape of certain deposits on the range, which have their longer dimensions parallel to the strike of the layers of the iron-formation.

The ponding of the water and consequent overflow has still another effect. Where ponded the flow is governed by the point of lowest escape rather than by the shape of the impervious basement. When water is drawn off at the edge of a basin, the flow is greatest near the point of escape and diminishes in all directions away from that point. This statement is true, whether the bottom of the basin is flat or fluted; hence, in the Mesabi iron-formation, where the water is ponded, the flow is concentrated near the point of lowest escape regardless of whether this be over a syncline or anticline provided both are below water-level. The lowest point of escape is likely to be over synclines, but the surface erosion, both by glacial and meteoric agencies, has been such that this is not always the case. For this reason it is not certain that iron-ore deposits near the edge of the Virginia slate or near the edge of interstratified slate-layers may not have developed along arches as well as in synclines of the iron-formation.

The above facts are intimately related to the problem of finding ore under the solid black Virginia slate. The question is frequently asked, is there any reason why ore shall not be found under the black slate? The absence of ore under the slate has not been demonstrated by actual drilling; only a comparatively few holes have penetrated any considerable thickness of the Virginia slate and entered the iron-formation below. Yet such holes as have been put down have revealed

ore only near the slate-margin and frequently of low-grade. In several cases, the iron-formation beneath the slate has been shown to be of a green, unaltered variety, indicating that the alteration necessary for the development of ore-deposits has not gone far. If the development of the ore is dependent upon a vigorous circulation, and this vigorous circulation is lacking under the Virginia slate because of the ponding, we have here an adequate cause for the non-existence of ore-deposits under the black slate. Yet, further work may show that other factors have entered; and, considering the extent and value of the new iron-bearing territory, which would be thrown open were ore found under the Virginia slate, additional actual drilling seems to be advisable.

In the Gogebic district, while the impervious basement has been the controlling factor in the concentration of waters, and consequently of the ores, faulting through the dikes has afforded free passages for waters which have been taken advantage of, with the result that the ores follow such faulting-planes and are not uniformly confined to positions on the impervious troughs.

In Figs. 1, 2, 3 and 4, it will be noted that, for all of the districts except the Mesabi, the vertical element in the distribution of the ores is an important one. In the Mesabi district the horizontal element is the greatest one in most cases. Here, a single ore-body or a group of ore-deposits may give practically a continuous surface of iron-ore for several miles, with a depth ranging from a few feet to 400 ft. or more. In the other ranges a depth of ore of 1,000 ft. is common and 2,000 ft. has been exceptionally reached. It is not unlikely that in some places, particularly the Gogebic district, the ores will be found to greater depth, although the lower limit is well determined for the most part. Theoretically, the lower limit of the ore-bodies ought to be the lower limit of the active circulation of oxidizing waters from the surface. In the Mesabi district the proportion of the area of the ore-bodies appearing at the rock-surface, to that of the iron-formation as a whole, is about 8 per cent. for the productive part of the district, and 5 per cent. for the entire district. For the other districts of the Lake Superior region, the area of the iron-ore deposits is far less than this percentage of the area of the iron-formation as a whole. In bulk, the percentage of ores to the iron-formation is much smaller

throughout the Lake Superior country, for it will be remembered that the ores are essentially surface-alterations and are therefore well represented at the surface.

The alteration of the iron-formation, resulting in the concentration of the iron-ores or in the development of ferruginous cherts and jaspers and amphibole-schists, has taken place in different geological periods under various conditions, with a result that the ores of each of the districts, as well as of different parts of the same district, show considerable lithological variety. The same ingredients—iron oxide and silica—appear here mechanically combined as highly crystalline jasper, there in the hydration as a soft ferruginous chert, or both mechanically and chemically combined as an amphibole-magnetite schist. The iron-oxide may appear here as a brilliant specular hematite or magnetite, and there as a soft granular hematite or limonite. The ores of the Mesabi district are soft and granular and associated with ferruginous cherts. At the east end they become amphibolitic, magnetitic and non-productive. The ores of the Gogebic district are of a similar nature and become amphibolitic, magnetitic and non-productive at both the east and west ends of the district. The ores of the Vermilion district are hard, blue and red ores, at Ely, brecciated, associated with jaspers. The ores of the Marquette district comprise hard blue ores and brilliant specular ores associated with jaspers, called "hard-ore jaspers," soft ores associated with ferruginous cherts, or "soft-ore jaspers," and with underlying slates, and at the west end of the district, magnetite and specular hematite ores associated with jaspers and with amphibole-magnetite rocks.

Without going into the variable conditions in the several districts and the varying geological history of the different ores and rocks, it may be said that, so far as the alteration of the iron-formation has proceeded continuously under the influence of surface-waters without interruption by igneous activity or orogenic movements, the soft ores and ferruginous cherts have resulted. So far as these have been subsequently under deep-seated conditions of alteration, they have become dehydrated into hard red and blue specular ores and brilliant jaspers. This phase of the alteration did not require the agency of surface oxidizing-waters. So far as the alteration of the original iron-forma-

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tion took place within the sphere of influence of great intrusive masses where the waters were heated and oxygen was not abundant, or under similar conditions developed by deep burial and orogenic movement, the iron oxide and silica of the formation combined with small amounts of other substances to form ferrous silicates, and the ferrous iron was oxidized to magnetite, making one of the variety of rocks usually described as amphibole-magnetite schists.

In the discussion of the development of the ores, we have begun with the original rocks of the iron-formation, namely, the iron carbonates and greenalite rocks, containing minute amounts of sulphide, which constituted the formation when it was first deposited. The origin of these rocks themselves is a subject of absorbing interest, but it is a subject in which direct evidence, such as we have been dealing with, is lacking; and a subject, furthermore, of less practical importance and less direct bearing upon the study of the ores themselves. Certain facts are well known. Both the iron carbonates and the greenalites (and their altered equivalents) constitute a conformable part of a continuous sedimentary succession, being interbedded, overlain and underlain by fragmental rocks, such as quartzite and slate. They are themselves bedded. It is impossible to escape the conclusion that they are water-deposited sediments. It is, further, clear that they are not water-deposited sediments of an ordinary nature. They are not fragmental; their nearest analogues are chemical sediments, such as limestones.

From here on in our explanation we must depend rather upon analogy with chemical sediments, such as limestone, and with iron compounds now being precipitated in bogs and lakes and elsewhere, than upon direct evidence in the formation itself. On this basis, the history of the development of these rocks, as outlined by Van Hise,[12] is as follows:

. . . "It is, however, my belief that the iron for the iron-bearing formations was largely derived from the more ancient basic volcanic rocks of the Lake Superior region. When the individual districts are taken up it will be seen that a greenstone, often ellipsoidal, in many places porous and amygdaloidal, in many places

[12] The Iron-Ore Deposits of the Lake Superior Region, by C. R. Van Hise, 21*st Annual Report, U. S. Geological Survey*, Pt. III., pp. 319, 320.

See also:

Monograph XLIII, U. S. Geological Survey, by C. K. Leith.

schistose, and rich in iron, is the most characteristic rock of the Archean, and that similar rocks occur abundantly in the Huronian. Where these igneous rocks were adjacent to the seas they would be leached by the underground water and the iron transported to the adjacent seas. It is probable that to some extent this leaching process also went on below the waters of the sea. The iron was probably transported to the water mainly as carbonate, but to some extent as sulphate. The carbonate would there be thrown down by oxidation and hydration as limonite, and the sulphate in part as basic ferric sulphate. Much of the sulphate was probably directly precipitated as sulphide by the organic material. The limonite would be mingled with the organic matter which was undoubtedly present, as shown by the associated carbonaceous and graphitic shales and slates. When deeply buried the organic matter would reduce the iron sesquioxide to iron protoxide. By the simultaneous decomposition of the organic matter carbon dioxide would be produced, which would unite with much of the protoxide of iron, producing iron carbonate. The sulphate of the basic ferrous sulphate would be reduced to the sulphide by the organic material, thus producing the pyritic carbonates. Where the iron was brought to the water mainly as sulphate the direct reduction of this salt by organic matter would form iron sulphide with little or no carbonate. Simultaneously with the production of these substances chert was formed, probably through the influence of organisms.[13]

"Some of this silica would unite with a part of the protoxide, producing ferrous silicate. More or less mechanical sediment would also be laid down. Thus the original rocks—the cherty iron carbonates, the ferrous silicate rocks, and the pyritic cherts—would be produced.

"It has chanced that at three different periods in the history of the Lake Superior region, these processes of the development of the original rocks of the iron-bearing formations have occurred extensively. While this might at first be thought remarkable, there is no good reason for thus regarding it. At some time during each of the Archean, Lower Huronian and Upper Huronian periods the quiescent conditions of chemical and organic sedimentation have occurred, and since the iron-bearing volcanic rocks were each time available for the work of underground waters and sea-waters, naturally iron carbonate and the other original rocks have been produced. In each period the source of the material and the process of its formation were essentially the same."

Time of Concentration.

The concentration of the ores of the Lake Superior region was far advanced before Cambrian time, as shown by the existence of ore and other iron-formation boulders, derived from the pre-Cambrian, in Cambrian conglomerates. For each of the districts the particular time of concentration has been more closely calculated, but this is a subject which would require a longer discussion than the scope of this paper warrants, and

[13] The Penokee Iron-Bearing Series of Michigan and Wisconsin, by R. D. Irving and C. R. Van Hise: *Monograph, U. S. Geological Survey*, vol. xix., 1892, pp. 246–253.

Fossil Medusæ, by C. D. Walcott: *Monograph, U. S. Geological Survey*, vol. xxx., 1898, pp. 17–21.

the reader is referred to Van Hise's general paper already cited.

Topographic Relations of the Ores.

With very few exceptions, the ore-deposits of the Lake Superior region lie either on the slopes or at the foot of conspicuous ranges or hills. This has been explained by Van Hise as due to the concentration of ores through the circulation of ground-waters. Topographic elevations have given the waters sufficient head to search the ground on their slopes and perhaps at the base of the slopes. On the slopes the movement of the water is largely downward and more or less direct from the surface, thus carrying an abundance of altering agents, particularly oxygen and carbon dioxide; while in intervening low-lying areas, the waters escape with a lateral and upward movement after a longer underground journey, during which they have lost considerable proportions of the agents which alter the iron-formation to ores. Van Hise holds that, in the latter positions, the ores have not developed so abundantly as on the slopes. The present topography is, in many places, not the same in detail as the topography which existed at the time the ores were concentrated; and accordingly it is not safe, in discussing the relations of the ores to the topography, to consider too small topographic units. Believing that the present major topographic conditions represent, at least in part, the past conditions, Van Hise has discussed in some detail the relations of the Lake Superior ores to the particular topographic features of the different districts. In one or two cases, and especially in the Gogebic district, the topographic units selected for discussion may have been too small, and this has resulted in criticism of the entire theory. It is believed that his main conclusions as to the relations of the ores to the major topographic features have been confirmed, rather than disproved, by recent work.

Present Studies of the Origin of the Ores.

The ores of the Lake Superior region have been shown, in certain districts, to have been developed from the alteration of iron carbonate, in other districts from the alteration of iron silicate, and in others, from both. In the Marquette, Gogebic, Vermilion, and Crystal Falls districts, the original rock has

been described as iron carbonate. In the Mesabi district, the original rock has been described as consisting of ferrous silicate or "greenalite" granules principally, but with subordinate amounts of iron carbonate. In the Felch Mountain and Republic areas, the presence of granules similar to the Mesabi granules has been noted. In the Menominee district, both iron carbonate and silicate granules have been supposed to yield the ore.

The vast scale on which the alteration of ferrous silicate granules has occurred in the Mesabi district, together with the evidence of the somewhat wide-spread distribution of such granules in unknown but small quantity, has led to a re-examination of the ores and rock of the remaining districts, with the result that evidence of the prior existence of granules has been found also in both the Gogebic and Crystal Falls districts. So far as the re-examination has gone, however, it tends to confirm the essential correctness of the determination of iron carbonate as the original iron-formation rock for these districts.

In the new Animikie iron-range, on the northwest coast of Lake Superior, the eastern continuation of the Mesabi range, original and secondary iron carbonate and pseudomorphs after greenalite are found so well exposed and so closely associated that it is hoped that the study of this district now in progress will furnish decisive evidence of the real relations of these two substances.

In the new Baraboo iron-range of Wisconsin, which is of pre-Cambrian age and similar in many respects to the Lake Superior deposits, Weidman has attempted to show that the ores are original bog-deposits, which have become dehydrated. His conclusion does not necessarily affect the remaining Lake Superior ores, but the similarity in geology is so close that, until the contrary is proved, it is believed that the explanation applied to one region will apply substantially to others. Reasons are given on a subsequent page for believing that his explanation is not a true one.

Experimental work in the laboratories of the University of Wisconsin shows the great ease of the alteration of the iron carbonates through the agency of water. In a few hours this substance becomes coated with hydrous iron oxide when treated with warm water containing only small amounts of oxygen de-

rived from contact with the air. Iron silicate has been found to be much more refractory, but still has yielded slightly to the action of ordinary water. Quantitative results are looked for at an early date. Analysis of mine-waters from the Lake Superior region as a whole, it is hoped, will yield results indicating the manner in which the ores and rocks of the iron-formation have been altered.

The form in which the phosphorus occurs is not definitely settled. Some of it is certainly in the form of apatite. But many ores, and especially Mesabi ores containing phosphorus, apparently do not contain apatite. The association of phosphorus with aluminum, both in ores and in other phases of the iron-formation, suggests the possibility that the phosphorus is chemically combined with aluminum. The solubility of the phosphorus compounds in the ores is still a mooted question. Incidents may be cited of the remarkable change of phosphorus-content in stock-piles and mines, because of the washing of surface-waters; and in drilling, allowances are frequently made for changes in phosphorus-content in washing. Whether this is mechanical or chemical, its extent and its commercial importance are yet to be decided. It is hoped that investigations now in progress will settle these questions.

Iron-Ranges of Recent Discovery.

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[The portion here omitted contains a description of the Baraboo range, of south central Wisconsin, where, associated with pre-Cambrian quartzites, beneath the Paleozoic rocks, slate, dolomite, and iron-ore occur. The district has been described in *Bulletin* xiii. of the Wis. Geol. and Nat. Hist. Survey (1904), by Dr. Samuel Weidman. The iron-ore is low-grade (below 55 per cent.) Bessemer hematite, with a little limonite, associated with and grading into "dolomite, cherty ferruginous dolomite, ferruginous chert, ferruginous slate, and ferruginous dolomitic slate." It is stratified conformably with the rocks below and above it. For the following reasons, Dr. Weidman thinks the Baraboo ores are bog-deposits, subsequently dehydrated.]

"1. The iron-ore deposits are bedded and, to all appearances, stratified like other sedimentary deposits.

"2. The stratified iron-ore deposits are not set off sharply from the surrounding associated stratified rocks, such as slate, chert and dolomite, but grade into them through all possible gradations. The iron-ore is not especially associated with any particular kind of the various rocks adjacent, and the stratification of these various kinds of rocks is always conformable to that of the iron-ore. Since the slate, dolomite and chert are original sedimentary deposits, and since the iron-ore grades into them and is conformable to them, it is believed that the iron-ore has the same origin as these conformable interstratified deposits of related rock.

"3. That the physical conditions in the district at the time the iron-formation was deposited were favorable for the formation of such shallow-water deposits as iron-ore is indicated by the presence of sun-cracks in the rocks of the iron-formation immediately adjacent to the iron-ore and also by the presence of carbonaceous material, probably decayed vegetable matter in the iron-ore and associated ferruginous rocks. Furthermore, the rapid alternation in the various strata of the iron-formation indicates changing conditions of sedimentation,—a common characteristic of shallow-water deposits, and the composition of the iron-bearing formation itself, with its chert, carbonate rock and slate, is identical with the composition of shallow-water deposits being formed to-day.

"4. That the iron-ore deposits originated long antecedent to the folding and fracturing of the iron-formation and the deposition of the mineral veins is shown by the fact that the strata of iron-ore are generally folded, crumpled and fractured, and that the mineral veins cut across the stratification and also across the folds of the iron-ore and associated rocks. The folding of the ore-deposits appears to conform in all respects to the folding of the associated rocks, and the ore-deposits appear to have the position and distribution which they should have if formed before the general folding of the pre-Cambrian formations into their present position took place.

"5. The change in the ore subsequent to its original deposition as limonite, as shown by the microscopic and chemical study of the rocks, is believed to be mainly a change to hematite by dehydration of the limonite under deep-seated conditions of metamorphism. This change is exactly parallel to the dehydration of the original clay-minerals of the gray Seeley slate-formation and of the clay-minerals in the slate-phases of the iron-formation, which now contain very little water of constitution, only 2 or 3 per cent., but which originally must have contained from 10 to 25 per cent. This change of limonite by dehydration is also analogous to the probable dehydration of the original siliceous deposits now constituting the chert layers.

"The geological data which led the writer to believe that the Baraboo iron-ore was very probably deposited as limonite under conditions similar to those under which bog- and lake-ore are formed to-day, and later merely partially dehydrated to form hematite, have just been briefly outlined. The principal evidence believed to be directly opposed to the theory of the secondary development of the iron-ore as replacement- and alteration-deposits by work of the underground water is mainly furnished by the character of the work of the underground water at present, as indicated by its chemical composition, and by the work of the ground-water of the past, as indicated by the character and composition of the mineral veins in the ore and associated rocks.

"From the study of the composition of the ground-water now circulating through the iron-bearing rock and associated formations in the district, and its comparison with that of ground-water outside the district and with river-waters and with chalybeate mineral waters, it has been concluded that very probably the present work of the ground-water in the iron-formation is not that of depositing iron-ore. It is quite generally accepted that mineral veins are deposited from underground water circulating through fractures in rocks; and the fact that the mineral veins in the iron-ore and associated rocks are largely quartz and not iron-ore is interpreted as evidence that the work of the ground-water of the past was very probably not that of depositing iron-ore. If the work of circulating ground-water of the past could have or did develop the iron-ore deposits, why should not the work be now in progress, since ground-water is now circulating through the ore-deposits and associated rocks as it has in the past; and if the iron-ore could have been or was developed by the work or agency of ground-water, why should

not the mineral veins that ramify through the ore-deposits and associated iron-bearing rocks be composed largely of iron-ore instead of quartz?"

As the Baraboo district is related geographically and stratigraphically with Lake Superior ore-bearing districts, Weidman's conclusion that the ores are original deposits immediately suggests that the same origin may hold for the ores elsewhere in the Lake Superior region, or, vice versa; and that explanations of the secondary origin of the Lake Superior ores may really apply in the Baraboo district. It is believed that Weidman has not proved the Baraboo ores to be an original deposit, for the following reasons:

His arguments 1, 2 and 3, without change, may be used equally well in support of a theory of secondary concentration from an originally deposited chemical sediment—iron carbonate or iron silicate—described as laid down in shallow waters.

No evidence is presented in support of argument 4. The secondary alteration of previously folded and contorted iron-formations to iron-ore, with the retention of all the folded and contorted structures, is the common feature for the Lake Superior country. Accompanying and following this change, there has been some additional folding, followed in some cases by an introduction of normal mineral veins, but usually it has been a minor phenomenon. The fact of the folding and contortion of iron-formation layers could not be accepted elsewhere in the Lake Superior country as evidence of the subsequent occurrence of the major folding.

The argument that the presence of quartz-veins shows that quartz only, and not iron-ore, has been introduced or concentrated subsequent to the deformation, it is believed, will not stand analysis. In the Lake Superior region, abundant evidence may be presented to show that quartz-veins have developed both before and after the concentration of the iron-ore, and I know of no criteria that will enable one to say that the presence of quartz, rather than iron-ore, in particular fractures or veins, proves or disproves the secondary origin of the ore. In the Vermilion district, minute veins of ore may be seen crossing both quartz-veins and an earlier concentration of the ore, and in turn are crossed by later quartz-veins.

The dehydration of limonite (5) has probably occurred, but it would make little difference whether the limonite were an original deposit or were itself a secondary alteration.

The argument that the composition of the waters seems to show that ore-concentration is not at present occurring is beside the mark when we remember that for the Lake Superior region as a whole, and hence for the Baraboo district itself until the contrary is proven, the concentration of the ores was largely finished before Cambrian time. The conditions at that time doubtless differed widely from present conditions, but even admitting that they are similar, the fact that waters from the iron-formation, which have been analyzed, contain no ingredients different from the surface-waters of the region, does not show that they may not still be doing work. Van Hise has emphasized the fact that the ordinary surface-waters are the ones that do the work, and that the development of iron oxides from iron carbonates and iron silicates is the normal work of percolating-waters for the belt of weathering in general. The presence of silica in the Baraboo waters shows that silica is being carried away from this general zone or region, and there is every reason to believe that it may be carried as well from the ore as from the overlying sandstone. Certainly it could not be assumed that the silica contained in the water, notwithstanding the fact that it is no more abundant in mine-waters than elsewhere, might not be coming from the ores themselves, thus enriching them. It is believed, also, that the process of alteration has gone so far in the mines from which the waters were secured, that the waters now circulating there are, for the most part, in contact with oxidized products—the end-products of alteration under such conditions—and that they could scarcely be expected to contain any considerable amounts of ferrous compounds. It is not at all certain that waters, working through less-altered parts of the formation, either in the past or elsewhere in this district, might not show a different composition.

Finally, Weidman's theory would require that, after straightening out the secondary folds and contortions, the iron-ore should lie in a continuous even bed or layer, having only such irregularities as would result from uneven deposition in shallow waters. If, in the Lake Superior region as a whole, the iron-formation layers should be straightened out, the resulting bed or layer would have strange shapes indeed, and would here and there end abruptly along the strike or dip, against other phases of the iron-formation or even against a dike or boss of greenstone. (See Fig. 1.) Indeed, Weidman's theory is

squarely opposed to nearly all conceptions of the structural relations of the ores to the adjacent rocks, worked out independently for each of the Lake Superior districts, where exploitation has gone far enough to allow of satisfactory study. It is believed that these structural facts, worked out for the region as a whole, will apply in the Baraboo district itself, so far as the facts are known in the present state of exploration.

The ores thus far found have been along the eroded edges of the iron-formation. Attempts to locate the ore in the center of the great Baraboo valley beneath the dolomite have met with failure. Straightening out the folds in the iron-ore bodies, and reproducing the original attitude and distribution, the iron-ore deposits would appear, so far as is now known, as a series of lenses, limited by dolomite or feathering-out beneath it, down the dip, in the direction of what is now the center of the valley. On Weidman's theory, the ore might be found anywhere beneath the dolomite, and its truncation by an erosion-surface would be purely a matter of accident. It must be admitted that drilling has not gone sufficiently far to prove that the iron-ore lenses uniformly reach the pre-Cambrian erosion-surface at some point; but sufficient drilling has been done to lead certain mining engineers of the district and me to conclude that the evidence is strongly in favor of this view and that the normal Lake Superior conditions here prevail.

While it is believed, for the above reasons, that Weidman's conclusion as to the origin of the Baraboo ores is not supported by the evidence he has presented, the fact that the ore grades into, and is overlain by, dolomite—a unique occurrence for the Lake Superior region—would make it easy to accept an explanation of the origin of the Baraboo ores different from that applied to the remaining Lake Superior ores, if sufficient evidence be presented; and such acceptance would not necessarily imply a revision of views of the secondary origin of the remaining Lake Superior ores.

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[The portion here omitted gives brief accounts of the Cuyuna range in Crow Wing county, Minn. ("containing ore of possible commercial value," and possibly of Archean, Middle Huronian or Upper Huronian age), and the Animikie range, extending NE. from Gunflint lake along the international boundary to the east end of Thunder bay, and regarded as an eastward continuation of the Mesabi. The paper ends with a statement of the work which must still be done, before the complex problems of the general and the economic geology of the Lake Superior region can be regarded as completely solved.]

No. 26.

The Geological Relations of the Scandinavian Iron-Ores.

BY PROF. HJALMAR SJÖGREN, PH.D.,* STOCKHOLM, SWEDEN.

(Toronto Meeting, July, 1907. *Trans.*, xxxviii., 766.)

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AMONG the feldspar-rocks there are certain types which occur constantly in different areas—viz., the amphibolitic plagioclase-rocks and the granulitic rocks composed of quartz and alkaline feldspars. Among the latter soda-granulites as well as potash-granulites are met with; also the corresponding gneisses occur.

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GROUP I.—THE ORES OF THE ARCHÆAN CRYSTALLINE SCHISTS.

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The Rocks.

The ore-bearing rocks of the ore-province of central Sweden are chemically and petrographically unlike the more monotonous gneiss- and granite-areas which surround them. On the whole, they constitute a quartz-feldspar formation in which purer quartzitic rocks, limestones, "*skarn*" rocks and ore-bodies are very subordinate members. (*Skarn* is the Swedish name for rocks of varying composition, mostly consisting of lime, magnesia, iron, and alumina silicates of the pyroxene, amphibole, and garnet groups; as secondary minerals, epidote, chlorite, biotite, and talc occur. The *skarn* is scarcely an independent rock but is connected with the ore-deposits. It is formed through an interchange between the silica of the quartz-feldspar rocks and the basic constituents of the ore-formation.)

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[ABRIDGED SUMMARY.—The amphibolites must be considered as stretched and dynamo-metamorphosed dioritic rocks. The granulites are divided into two groups, one showing predominant plagioclase, the other equal or predominant orthoclase. Evidently, the iron-ore deposits are connected in some way with the

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rocks of granulitic structure. This structure is most probably due, in general, to a recrystallization, under stress and movement, within the anamorphic zone of depth. "Simultaneously with the mechanical deformation of the rock-masses

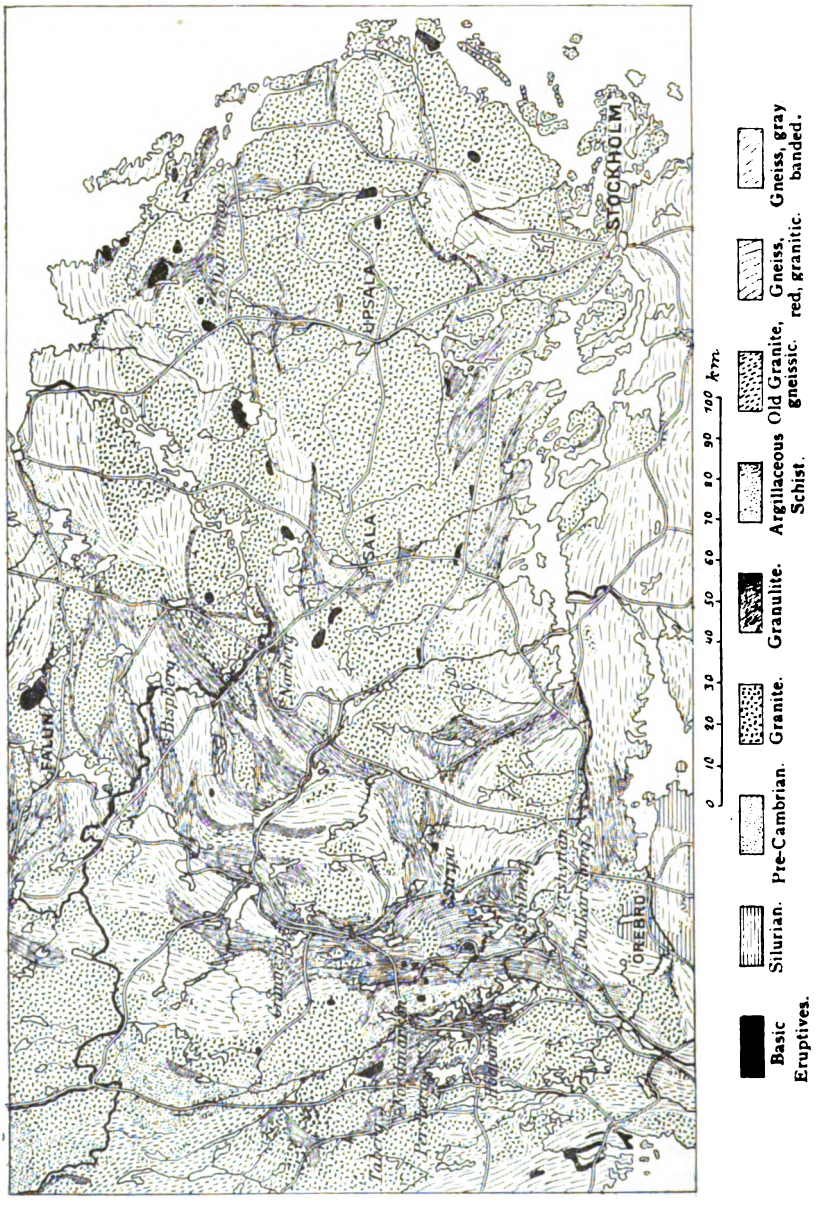

FIG. 1.—ORE-PROVINCE OF CENTRAL SWEDEN.

there has been also a supply of iron-bearing magmatic material by solutions, imparting to the ore-deposits their present peculiar epigenetic characters." Numerous pegmatitic dikes, penetrating both ore and rock, are to be considered

as crystallized from aqueo-igneous solutions in contraction-fissures, during the cooling of the rock. Stripes, stratification, contortion, and even brecciation of the country-rock near the ore-body, indicate the metasomatic deposition of the latter in shear-zones, or in portions of the original rock contracted in volume by the chemical changes involved, as well as fractured by movement. There is also a linear or stretched structure, sometimes conformable to the pitch of the ore-bodies. The amphibolites and a great part of the granulites seem to be igneous rocks of deep-seated origin.

The ores are of five types: (A) Ores carrying apatite, disseminated or in stripes, with low percentage of silica and feldspar. These were originally magnetite, but have been altered in many places to specular hematite by a process which simultaneously reduced the proportion of apatite. They are products either of magmatic differentiation in the granulite or of metasomatic replacement of feldspar-rock by iron-bearing solutions in the anamorphic zone. The constant large amount of apatite favors the former hypothesis. (B) Mixed hematites and magnetites, nearly related to the preceding, and evidently formed through injection of iron-bearing solutions and partial replacement—the ore being therefore much younger than the country-rock. (C) Quartz-banded ores, chiefly specular hematites. The alternation of ore and gangue is often, but not always, as definite as in the jasper-banded ores of Lake Superior. This structure has been generally regarded as due to a primary stratification, on which hypothesis the ores must have formed by the alteration of stratified rocks. But it seems more probable that the structure is a secondary feature, produced during the replacement process. (D) The "*skarn*" ores, rich magnetites, accompanied and connected by beds of "*skarn*" minerals (see definition of "*skarn*," on a preceding page). They have often been formed by metasomatic replacement of limestone and dolomite, ore and gangue-minerals being thus younger than the country-rock. (E) Limestone-ores, occurring in or with limestone and dolomite, of which they are metasomatic replacements.]

The Origin of the Ore-Deposits.

During the last century the ores of this group were regarded by Swedish geologists as sedimentary deposits, laid down together with the over- and underlying granulite formation. Such opinions were advocated by A. Erdmann, Anton Sjögren, A. E. Törnebohm, B. Santesson, and others; among the Norwegian geologists Vogt has with eagerness developed this theory.[3] Only with respect to the Gellivare ores, opinions were much divided, and several geologists—*e.g.*, Lundbohm, v. Post and Löfstrand—believed them to be of igneous origin.

[3] See, for instance, J. H. L. Vogt, De lagformigt optraedende jernmalmforekomster, *Geologiska Föreningen Förhandlingar*, vol. xvi., p. 275 (1894); Dunderlandsdalens jernmalmfelt, *Norges Geologiska Undersögelse*, No. 15, pp. 56 to 63 (1894); Om de lagrade jernmalmsfyn-digheternas bildningssätt, *Werml. Bergsmannaför Ann.* (1896).

The same opinion has also been expressed by several foreign geologists, for instance, De Launay, *Annales des Mines*, Tenth Series, vol. iv., pp. 49 to 209 (1903), as well as in the German treatises on Ore-Deposits by Beck (1901), and Stelzner-Bergeat (1906).

Since 1890, the present writer has in several papers argued that metasomatic processes undoubtedly played a prominent part in the formation of these ores, and has been able to point out several analogies with the iron-ores of the Lake Superior region.

In this paper I shall attempt to show that the metasomatic processes must have taken place, not in the surface-zone but in the anamorphic zone, and that the ores bear fully, in their mineralogical features and association, characters of formations of the deep-seated zone.

In several cases, it may not be possible to determine whether the original iron-bearing material was the product of primary magmatic differentiation, as in the apatite-ores, or iron-bearing magmatic solutions producing metasomatic deposits, as in the lime- and *skarn*-ores, or possibly altered chemical sediments, as in the quartz-banded-ore type.

The iron-bearing solutions may frequently have been of magmatic origin, thus carrying iron-bearing material from below; or it may be that the very small amount of water contained in the rocks was sufficient, under the condition of dynamic metamorphism in the anamorphic zone, to collect and concentrate the iron particles. The occurrence of ore-deposits in connection with surface-rocks, above pointed out, and their absence in the greater granite laccolites seems to prove that the deposits are formed in a depth less than that in which the granite consolidated, but still in the anamorphic zone.

Arguments Against the Sedimentation Theory.—That these deposits are not sedimentary is indicated by the fact that the surrounding rocks are igneous. So long as the granulite of Grängesberg and Gellivare was considered a sedimentary rock, it was possible to ascribe the same nature to the ore-deposits. But this foundation of the sedimentary theory seems more and more to give way.

Again, the form of these ore-deposits differs as widely as possible from that of stratified bodies. They have been termed lenses, stocks, lineals, etc. In general, they are much more irregular than is consistent with a sedimentary formation. Sometimes these ores divide or branch into the surrounding rock (see Fig. 2, showing the central part of Dannemora), a feature which does not agree with any known form of primary sedimentation,

but must be interpreted as secondary. At other places, the ore incloses portions of the surrounding rock, which sometimes take the form of irregular sinuous bands, cutting obliquely through the ore from the hanging-wall to the foot-wall. (See Fig. 3, showing the central part of Grängesberg.) In such cases it appears that the overlying and the underlying rock, together with the narrow partition-walls between the ore-lenses, form " a continuous whole, pre-existing to the ore." This mode of occurrence also is incompatible with sedimentary deposition.

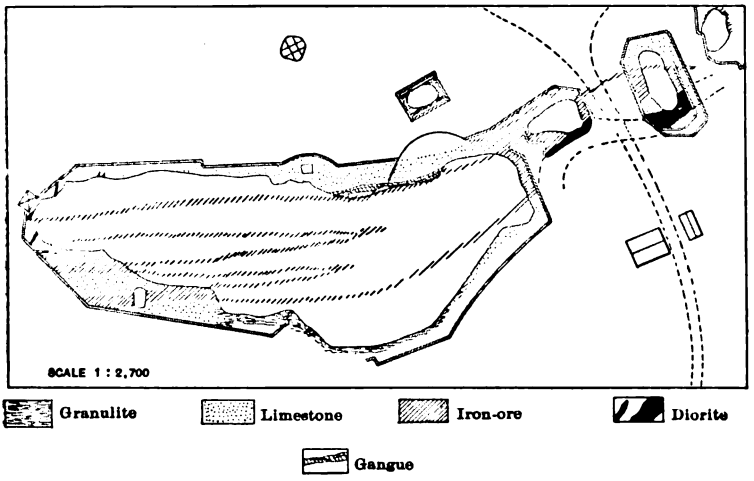

FIG. 2.—DANNEMORA MINE, CENTRAL PART.

In a few cases only, a structure resembling primitive stratification is met with; *e.g.*, in the banded quartziferous ores (type C), which for this reason possess special interest. The ores rich in silica and alumina (type B) sometimes present a schistose structure; but this is without any doubt a foliation caused by pressure.

Even where the stratified structure is present, we are not justified in concluding that the material is primitive; for in this case also, though retaining the original structure, it may have been subjected to subsequent metasomatic transformation. Thus the banded quartziferous ores may have originally consisted of alternating bands of a carbonate and of amorphous silica, since altered or replaced *in situ*.

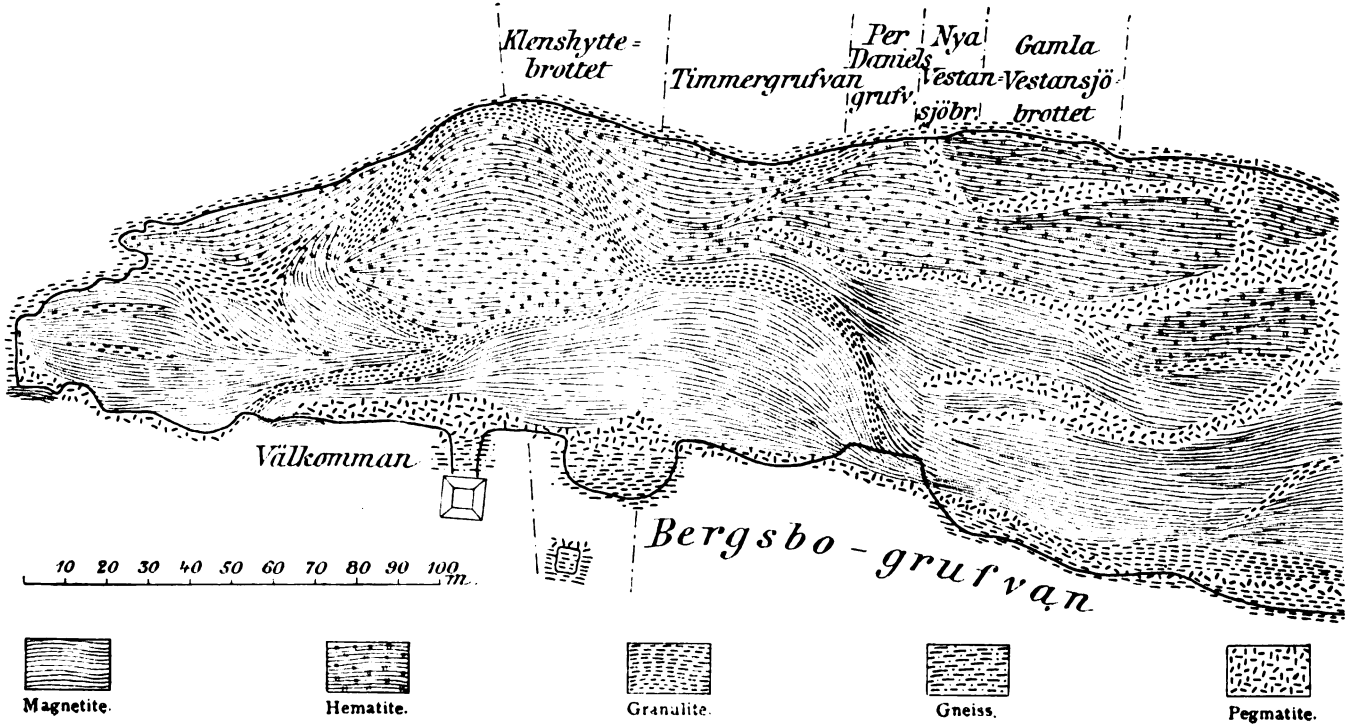

FIG. 3.—CENTRAL PART OF GRÄNGESBERG.

Concentration and Transformation Within the Deep-Seated Anamorphic Zone.—To this zone the rocks were transferred during the period of the plication, by which evidently a part were folded to a considerable depth, being at the same time subjected to dynamo-metamorphic alterations, which in many cases determined their present characters.

During this period the ores and the gangue were formed by thermal iron-bearing solutions acting under high pressure. To what degree these solutions were magmatic, carrying ore-substance from below, or to what degree the small amount of water contained in the rock was active, it is not possible to determine. In either case, the process was different from the action of solutions circulating in open channels. It consisted in a solution of the rock-substance, which was intensified by the stress and friction, according to the principle of Riecke, and also in an accumulation and concentration of the ore, the surface-tension operating to unite particles of the same substance.

The ore-material, participating in the plication process, with its upheavals, folding and dislocations of the strata, has suffered some mechanical changes. One of the effects which, in many cases at least, may be ascribed to the mechanical folding is the peculiar overlapping which many ore-bodies present. This may be a primitive form of metasomatic deposition, but may also be considered as a result of the mechanical displacement of an ore-layer. Through a number of inclined or even vertical planes of dislocation, the deposit has been cut into pieces, which have then been somewhat displaced in relation to one another. Often these dislocations can be pointed out only with difficulty, or not at all; they are more obvious when the iron-ore occurs associated with a limestone bed. (See Fig. 4, showing the plan of Ställberget.) The whole limestone horizon, with its accompanying iron-ore, is here fractured into several lenses, oblique to one another. The planes of dislocation have been effaced by the recrystallization of the granulite, and the schistose structure thereby developed, with its lamination running obliquely to the different lenses, which gives the appearance of being situated on different levels of the stratigraphical series.

Another mechanical effect of the rock-plication is the stretch-

ing of the surrounding rock, by which it has assumed a linear structure, a system of smaller folds, with the axis of folding parallel to the stretching, having often been formed at the same time. In many cases (*e. g.*, the Lekomberga mine in the parish of Ludvika, and the Smedje and Mossaberg mines in Striberg), a connection between the stretching of the rocks and the pitch of the ore-bodies is observable, the axis of the stretching coinciding with the direction of the pitch. Yet it cannot be assumed as beyond dispute that this connection is in every case

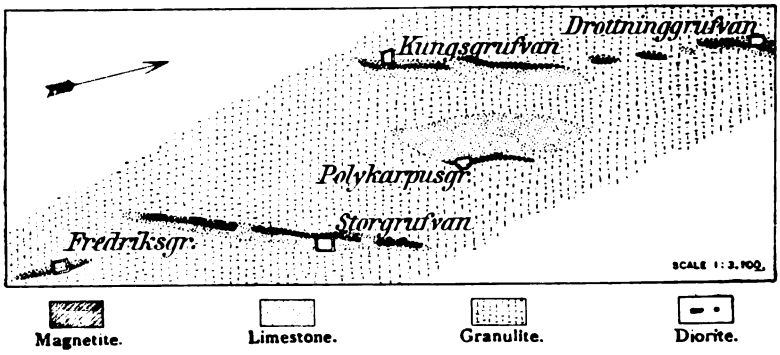

FIG. 4.—STÄLLBERG MINES.

due to a stretching of the ores themselves; it may also be explained as produced by the ferriferous solutions, chiefly following the directions indicated by the folds, formed simultaneously with the stretching of the rocks.

The stretching of the rocks has given rise to the characteristic form presented by the Swedish ores of this type, which form is evidently due to a factor acting in a vertical direction. This form is represented in Fig. 5, which is a longitudinal section of part of the Svartvik mines, according to B. Santesson. Sometimes this form will be developed into such an extreme type as that of the mine of Stora Malmsjöberg, in which the ore mined in 1898 had, according to H. Sundholm, a length of 15 m., a breadth of 12 m., and a depth of 150 meters.

The Chemical Changes.—These have been much increased, not only by the high temperature in the anamorphic zone, but also by the stress and mechanical deformation, which tends to increase the solubility of the ore-material, as well as of the rocks.

The more easily soluble limestones were especially adapted to take up the ore-deposition; and generally great changes and transfers of the ores to secondary places of deposition have taken place in them, depending on water-courses, impermeable sub-strata, etc. The concentration has occurred especially along folds, fracture-zones, fissure-systems, and contacts. Thus the ores assume the irregular, secondary forms characteristic of metasomatic deposits, as shown in Fig. 2, representing the central part of Dannemora.

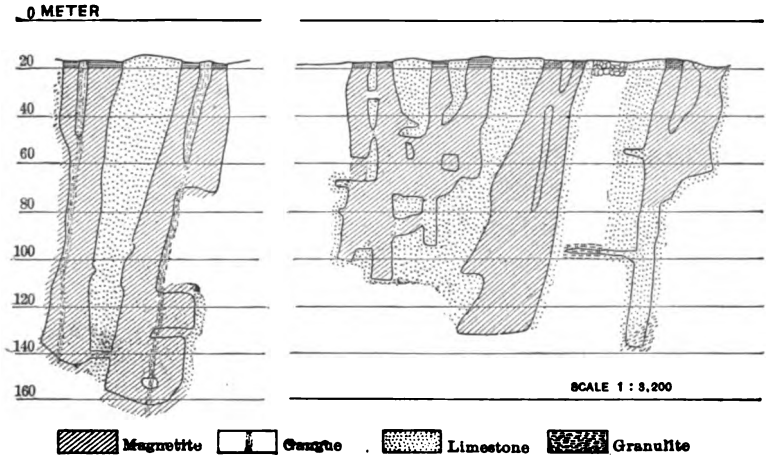

FIG. 5.—LONGITUDINAL SECTION OF THE SVARTVIK MINES.

Other instances of concentration by solutions are offered by the fairly numerous cases in which the ore proves to be younger than dikes which traverse it. Such an instance is the Timansberg, a deposit of type D, which is traversed by minor dioritic dikes. Of these, C. H. Vrang writes that "in their vicinity the ore increases considerably in thickness."[4] In the Krangrufva, in the Persberg district, the rich and pure ore is chiefly found on one side of a large diorite dike; a dislocation is out of the question, for the ore-bearing layer is also found on the other side of the diorite, but without equally distinct ore-concentration. H. V. Tiberg has described how, in the Gustavus mine of the Långban district, a deposit consisting of specular iron-ore and magnetite, with gangue, continues from the surface to a flat system of diabase apophyses occurring at a depth

[4] *Geologiska Föreningen Förhandlingar*, Stockholm, vol. ix., p. 244 (1887).

of from 54 to 60 m., on which the ore spreads like a cake, while below the diabase dikes the rock is dolomite only. In such cases the intrusive dikes have evidently preserved the underlying rock from transformation. A similar instance from Dannemora is mentioned by A. E. Fahlcrantz,[5] who says that over a dike of *hälleflinta* (felsite-porphyry) a band of iron-ore a few inches in thickness was met with, accompanying the *hälleflinta*. In this case, however, it is probable that the ore is a more recent formation; for the majority of the Dannemora ores are certainly older than the felsite-porphyries.

Many limestone beds have been largely, or even wholly, transformed into ores, especially of type D, the gangues of which, consisting of calcium and magnesium silicates, clearly indicate their origin.

At Utö it is questionable whether the concentration of the most prominent ore-deposit is not connected with the two traversing pegmatite dikes. The largest and deepest mines, which have followed the deposit down to a vertical depth of more than 200 m., are situated between these two pegmatite dikes; moreover, on the outer sides of the pegmatites there is a continuous ore-mass, which has been followed down to a comparatively great depth. At some distance from these dikes the ore has everywhere been less thick and less concentrated, and has, therefore, been mined on a small scale only. While the pegmatite dikes evidently originated at a great depth, it follows that the ore-concentration could not have been accomplished earlier than the submersion in the deep-seated zone.

The numerous mines of the Grängesberg, Blötberg, Fredmundsberg, and Gräsberg districts offer good opportunities to observe the relation between the pegmatites and the ores. The former occur here as dikes, partly traversing the ores, and partly parallel to the stratification, but in a manner which indicates that they are of later formation than the ores. Coarsely crystalline magnetite is often found in the pegmatite veins, indicating that the aqueo-igneous solutions giving rise to the pegmatite originated from the same source as the iron-ore.

In this connection attention may be called to the not uncommon fact that the ores of this type occur along contacts, gener-

[5] *Bihang till Handlingar Kongliga Svenska Vetanskaps-Akademie*, Stockholm, 4 (1876).

ally between limestone and granulite, but also along the contact with intrusive rocks. A marked instance of the former mode of occurrence is seen at Persberg (Fig. 6), where the upper ore-bearing horizon occupies a basin with granulite in the foot-wall and dolomized limestone in the hanging-wall. Similar instances

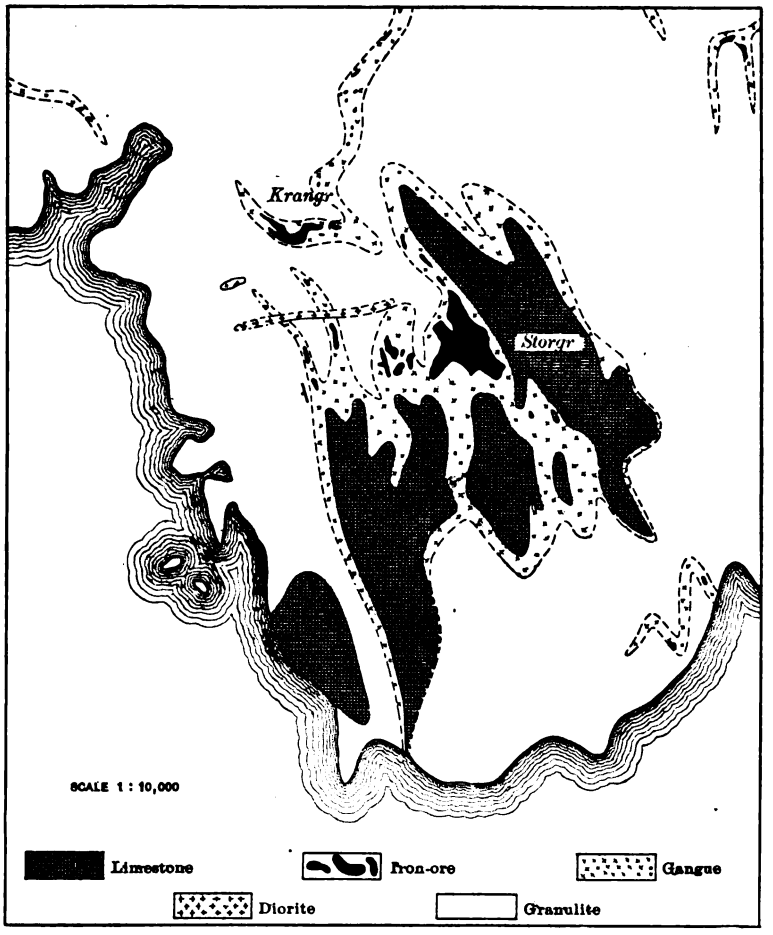

FIG. 6.—PERSBERG.

are found in several other ore-deposits of type D; *e. g.*, the Gåsgrufve mine and the Nordmark mines in Vermland, and Stenring and Ramhäll in Upland. In such cases the situation of the ores along the contact can hardly be explained by assuming them to be of primary origin; the only explanation possible is

squarely opposed to nearly all conceptions of the structural relations of the ores to the adjacent rocks, worked out independently for each of the Lake Superior districts, where exploitation has gone far enough to allow of satisfactory study. It is believed that these structural facts, worked out for the region as a whole, will apply in the Baraboo district itself, so far as the facts are known in the present state of exploration.

The ores thus far found have been along the eroded edges of the iron-formation. Attempts to locate the ore in the center of the great Baraboo valley beneath the dolomite have met with failure. Straightening out the folds in the iron-ore bodies, and reproducing the original attitude and distribution, the iron-ore deposits would appear, so far as is now known, as a series of lenses, limited by dolomite or feathering-out beneath it, down the dip, in the direction of what is now the center of the valley. On Weidman's theory, the ore might be found anywhere beneath the dolomite, and its truncation by an erosion-surface would be purely a matter of accident. It must be admitted that drilling has not gone sufficiently far to prove that the iron-ore lenses uniformly reach the pre-Cambrian erosion-surface at some point; but sufficient drilling has been done to lead certain mining engineers of the district and me to conclude that the evidence is strongly in favor of this view and that the normal Lake Superior conditions here prevail.

While it is believed, for the above reasons, that Weidman's conclusion as to the origin of the Baraboo ores is not supported by the evidence he has presented, the fact that the ore grades into, and is overlain by, dolomite—a unique occurrence for the Lake Superior region—would make it easy to accept an explanation of the origin of the Baraboo ores different from that applied to the remaining Lake Superior ores, if sufficient evidence be presented; and such acceptance would not necessarily imply a revision of views of the secondary origin of the remaining Lake Superior ores.

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[The portion here omitted gives brief accounts of the Cuyuna range in Crow Wing county, Minn. ("containing ore of possible commercial value," and possibly of Archean, Middle Huronian or Upper Huronian age), and the Animikie range, extending NE. from Gunflint lake along the international boundary to the east end of Thunder bay, and regarded as an eastward continuation of the Mesabi. The paper ends with a statement of the work which must still be done, before the complex problems of the general and the economic geology of the Lake Superior region can be regarded as completely solved.]

No. 26.

The Geological Relations of the Scandinavian Iron-Ores.

BY PROF. HJALMAR SJÖGREN, PH.D.,* STOCKHOLM, SWEDEN.

(Toronto Meeting, July, 1907. *Trans.*, xxxviii., 766.)

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AMONG the feldspar-rocks there are certain types which occur constantly in different areas—viz., the amphibolitic plagioclase-rocks and the granulitic rocks composed of quartz and alkaline feldspars. Among the latter soda-granulites as well as potash-granulites are met with; also the corresponding gneisses occur.

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GROUP I.—THE ORES OF THE ARCHÆAN CRYSTALLINE SCHISTS.

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The Rocks.

The ore-bearing rocks of the ore-province of central Sweden are chemically and petrographically unlike the more monotonous gneiss- and granite-areas which surround them. On the whole, they constitute a quartz-feldspar formation in which purer quartzitic rocks, limestones, "*skarn*" rocks and ore-bodies are very subordinate members. (*Skarn* is the Swedish name for rocks of varying composition, mostly consisting of lime, magnesia, iron, and alumina silicates of the pyroxene, amphibole, and garnet groups; as secondary minerals, epidote, chlorite, biotite, and talc occur. The *skarn* is scarcely an independent rock but is connected with the ore-deposits. It is formed through an interchange between the silica of the quartz-feldspar rocks and the basic constituents of the ore-formation.)

* * * * * * * * * *

[ABRIDGED SUMMARY.—The amphibolites must be considered as stretched and dynamo-metamorphosed dioritic rocks. The granulites are divided into two groups, one showing predominant plagioclase, the other equal or predominant orthoclase. Evidently, the iron-ore deposits are connected in some way with the

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rocks of granulitic structure. This structure is most probably due, in general, to a recrystallization, under stress and movement, within the anamorphic zone of depth. "Simultaneously with the mechanical deformation of the rock-masses

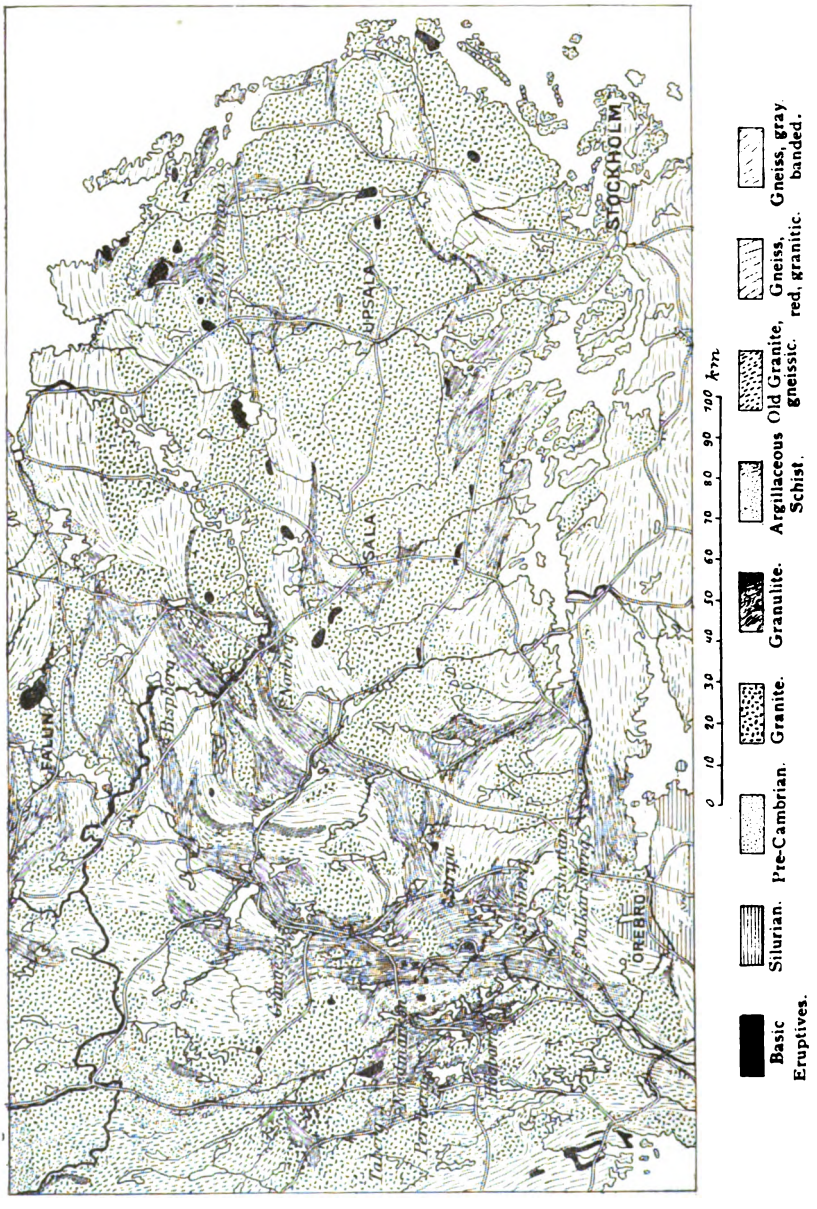

FIG. 1.—ORE-PROVINCE OF CENTRAL SWEDEN.

there has been also a supply of iron-bearing magmatic material by solutions, imparting to the ore-deposits their present peculiar epigenetic characters." Numerous pegmatitic dikes, penetrating both ore and rock, are to be considered

as crystallized from aqueo-igneous solutions in contraction-fissures, during the cooling of the rock. Stripes, stratification, contortion, and even brecciation of the country-rock near the ore-body, indicate the metasomatic deposition of the latter in shear-zones, or in portions of the original rock contracted in volume by the chemical changes involved, as well as fractured by movement. There is also a linear or stretched structure, sometimes conformable to the pitch of the ore-bodies. The amphibolites and a great part of the granulites seem to be igneous rocks of deep-seated origin.

The ores are of five types: (A) Ores carrying apatite, disseminated or in stripes, with low percentage of silica and feldspar. These were originally magnetite, but have been altered in many places to specular hematite by a process which simultaneously reduced the proportion of apatite. They are products either of magmatic differentiation in the granulite or of metasomatic replacement of feldspar-rock by iron-bearing solutions in the anamorphic zone. The constant large amount of apatite favors the former hypothesis. (B) Mixed hematites and magnetites, nearly related to the preceding, and evidently formed through injection of iron-bearing solutions and partial replacement—the ore being therefore much younger than the country-rock. (C) Quartz-banded ores, chiefly specular hematites. The alternation of ore and gangue is often, but not always, as definite as in the jasper-banded ores of Lake Superior. This structure has been generally regarded as due to a primary stratification, on which hypothesis the ores must have formed by the alteration of stratified rocks. But it seems more probable that the structure is a secondary feature, produced during the replacement process. (D) The "*skarn*" ores, rich magnetites, accompanied and connected by beds of "*skarn*" minerals (see definition of "*skarn*," on a preceding page). They have often been formed by metasomatic replacement of limestone and dolomite, ore and gangue-minerals being thus younger than the country-rock. (E) Limestone-ores, occurring in or with limestone and dolomite, of which they are metasomatic replacements.]

The Origin of the Ore-Deposits.

During the last century the ores of this group were regarded by Swedish geologists as sedimentary deposits, laid down together with the over- and underlying granulite formation. Such opinions were advocated by A. Erdmann, Anton Sjögren, A. E. Törnebohm, B. Santesson, and others; among the Norwegian geologists Vogt has with eagerness developed this theory.[3] Only with respect to the Gellivare ores, opinions were much divided, and several geologists—*e.g.*, Lundbohm, v. Post and Löfstrand—believed them to be of igneous origin.

[3] See, for instance, J. H. L. Vogt, De lagformigt optraedende jernmalmforekomster, *Geologiska Föreningen Förhandlingar*, vol. xvi., p. 275 (1894); Dunderlandsdalens jernmalmfelt, *Norges Geologiska Undersögelse*, No. 15, pp. 56 to 63 (1894); Om de lagrade jernmalmsfyn-digheternas bildningssätt, *Werml. Bergsmannaför Ann.* (1896).

The same opinion has also been expressed by several foreign geologists, for instance, De Launay, *Annales des Mines*, Tenth Series, vol. iv., pp. 49 to 209 (1903), as well as in the German treatises on Ore-Deposits by Beck (1901), and Stelzner-Bergeat (1906).

Since 1890, the present writer has in several papers argued that metasomatic processes undoubtedly played a prominent part in the formation of these ores, and has been able to point out several analogies with the iron-ores of the Lake Superior region.

In this paper I shall attempt to show that the metasomatic processes must have taken place, not in the surface-zone but in the anamorphic zone, and that the ores bear fully, in their mineralogical features and association, characters of formations of the deep-seated zone.

In several cases, it may not be possible to determine whether the original iron-bearing material was the product of primary magmatic differentiation, as in the apatite-ores, or iron-bearing magmatic solutions producing metasomatic deposits, as in the lime- and *skarn*-ores, or possibly altered chemical sediments, as in the quartz-banded-ore type.

The iron-bearing solutions may frequently have been of magmatic origin, thus carrying iron-bearing material from below; or it may be that the very small amount of water contained in the rocks was sufficient, under the condition of dynamic metamorphism in the anamorphic zone, to collect and concentrate the iron particles. The occurrence of ore-deposits in connection with surface-rocks, above pointed out, and their absence in the greater granite laccolites seems to prove that the deposits are formed in a depth less than that in which the granite consolidated, but still in the anamorphic zone.

Arguments Against the Sedimentation Theory.—That these deposits are not sedimentary is indicated by the fact that the surrounding rocks are igneous. So long as the granulite of Grängesberg and Gellivare was considered a sedimentary rock, it was possible to ascribe the same nature to the ore-deposits. But this foundation of the sedimentary theory seems more and more to give way.

Again, the form of these ore-deposits differs as widely as possible from that of stratified bodies. They have been termed lenses, stocks, lineals, etc. In general, they are much more irregular than is consistent with a sedimentary formation. Sometimes these ores divide or branch into the surrounding rock (see Fig. 2, showing the central part of Dannemora), a feature which does not agree with any known form of primary sedimentation,

but must be interpreted as secondary. At other places, the ore incloses portions of the surrounding rock, which sometimes take the form of irregular sinuous bands, cutting obliquely through the ore from the hanging-wall to the foot-wall. (See Fig. 3, showing the central part of Grängesberg.) In such cases it appears that the overlying and the underlying rock, together with the narrow partition-walls between the ore-lenses, form " a continuous whole, pre-existing to the ore." This mode of occurrence also is incompatible with sedimentary deposition.

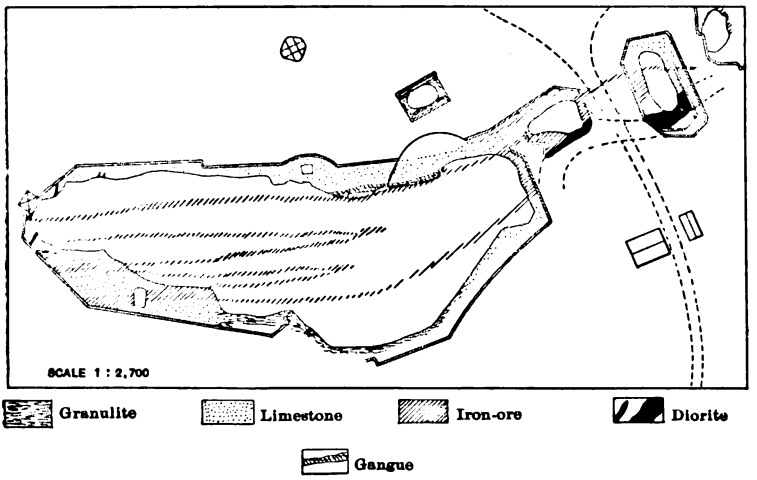

FIG. 2.—DANNEMORA MINE, CENTRAL PART.

In a few cases only, a structure resembling primitive stratification is met with; *e.g.*, in the banded quartziferous ores (type C), which for this reason possess special interest. The ores rich in silica and alumina (type B) sometimes present a schistose structure; but this is without any doubt a foliation caused by pressure.

Even where the stratified structure is present, we are not justified in concluding that the material is primitive; for in this case also, though retaining the original structure, it may have been subjected to subsequent metasomatic transformation. Thus the banded quartziferous ores may have originally consisted of alternating bands of a carbonate and of amorphous silica, since altered or replaced *in situ*.

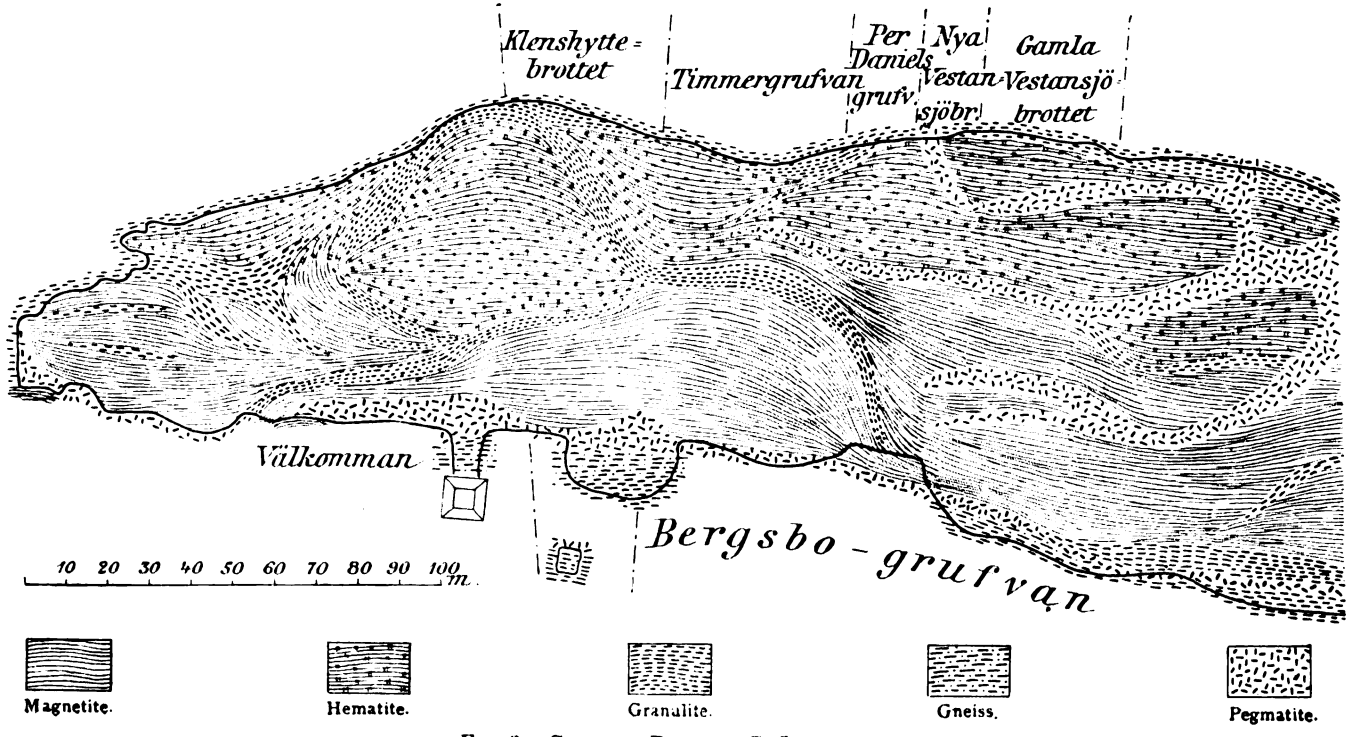

FIG. 3.—CENTRAL PART OF GRÄNGESBERG.

Concentration and Transformation Within the Deep-Seated Anamorphic Zone.—To this zone the rocks were transferred during the period of the plication, by which evidently a part were folded to a considerable depth, being at the same time subjected to dynamo-metamorphic alterations, which in many cases determined their present characters.

During this period the ores and the gangue were formed by thermal iron-bearing solutions acting under high pressure. To what degree these solutions were magmatic, carrying ore-substance from below, or to what degree the small amount of water contained in the rock was active, it is not possible to determine. In either case, the process was different from the action of solutions circulating in open channels. It consisted in a solution of the rock-substance, which was intensified by the stress and friction, according to the principle of Riecke, and also in an accumulation and concentration of the ore, the surface-tension operating to unite particles of the same substance.

The ore-material, participating in the plication process, with its upheavals, folding and dislocations of the strata, has suffered some mechanical changes. One of the effects which, in many cases at least, may be ascribed to the mechanical folding is the peculiar overlapping which many ore-bodies present. This may be a primitive form of metasomatic deposition, but may also be considered as a result of the mechanical displacement of an ore-layer. Through a number of inclined or even vertical planes of dislocation, the deposit has been cut into pieces, which have then been somewhat displaced in relation to one another. Often these dislocations can be pointed out only with difficulty, or not at all; they are more obvious when the iron-ore occurs associated with a limestone bed. (See Fig. 4, showing the plan of Ställberget.) The whole limestone horizon, with its accompanying iron-ore, is here fractured into several lenses, oblique to one another. The planes of dislocation have been effaced by the recrystallization of the granulite, and the schistose structure thereby developed, with its lamination running obliquely to the different lenses, which gives the appearance of being situated on different levels of the stratigraphical series.

Another mechanical effect of the rock-plication is the stretch-

ing of the surrounding rock, by which it has assumed a linear structure, a system of smaller folds, with the axis of folding parallel to the stretching, having often been formed at the same time. In many cases (*e. g.*, the Lekomberga mine in the parish of Ludvika, and the Smedje and Mossaberg mines in Striberg), a connection between the stretching of the rocks and the pitch of the ore-bodies is observable, the axis of the stretching coinciding with the direction of the pitch. Yet it cannot be assumed as beyond dispute that this connection is in every case

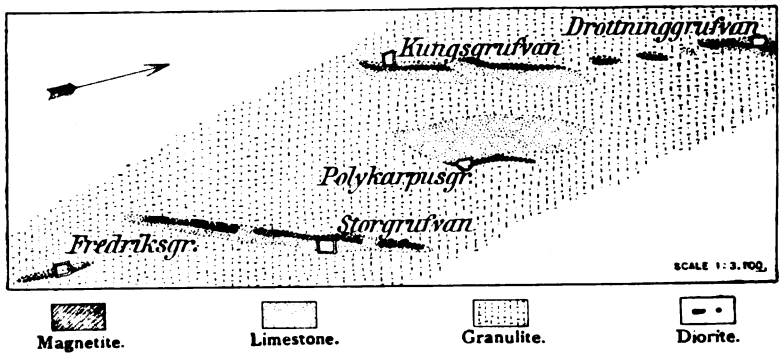

FIG. 4.—STÄLLBERG MINES.

due to a stretching of the ores themselves; it may also be explained as produced by the ferriferous solutions, chiefly following the directions indicated by the folds, formed simultaneously with the stretching of the rocks.

The stretching of the rocks has given rise to the characteristic form presented by the Swedish ores of this type, which form is evidently due to a factor acting in a vertical direction. This form is represented in Fig. 5, which is a longitudinal section of part of the Svartvik mines, according to B. Santesson. Sometimes this form will be developed into such an extreme type as that of the mine of Stora Malmsjöberg, in which the ore mined in 1898 had, according to H. Sundholm, a length of 15 m., a breadth of 12 m., and a depth of 150 meters.

The Chemical Changes.—These have been much increased, not only by the high temperature in the anamorphic zone, but also by the stress and mechanical deformation, which tends to increase the solubility of the ore-material, as well as of the rocks.

The more easily soluble limestones were especially adapted to take up the ore-deposition; and generally great changes and transfers of the ores to secondary places of deposition have taken place in them, depending on water-courses, impermeable sub-strata, etc. The concentration has occurred especially along folds, fracture-zones, fissure-systems, and contacts. Thus the ores assume the irregular, secondary forms characteristic of metasomatic deposits, as shown in Fig. 2, representing the central part of Dannemora.

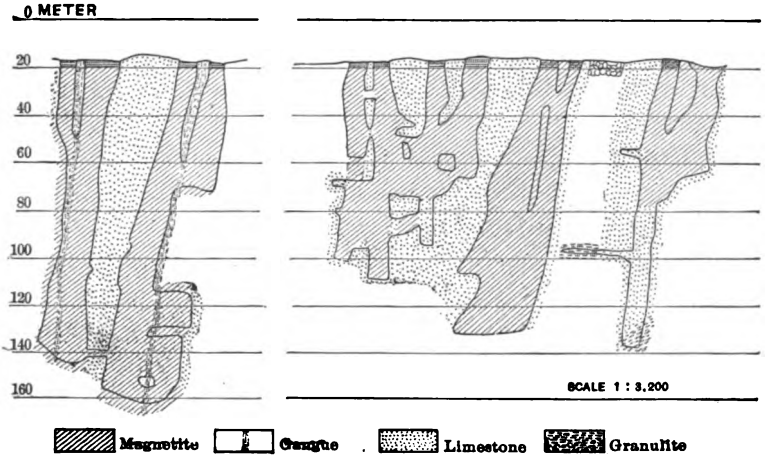

FIG. 5.—LONGITUDINAL SECTION OF THE SVARTVIK MINES.

Other instances of concentration by solutions are offered by the fairly numerous cases in which the ore proves to be younger than dikes which traverse it. Such an instance is the Timansberg, a deposit of type D, which is traversed by minor dioritic dikes. Of these, C. H. Vrang writes that "in their vicinity the ore increases considerably in thickness."[4] In the Krangrufva, in the Persberg district, the rich and pure ore is chiefly found on one side of a large diorite dike; a dislocation is out of the question, for the ore-bearing layer is also found on the other side of the diorite, but without equally distinct ore-concentration. H. V. Tiberg has described how, in the Gustavus mine of the Långban district, a deposit consisting of specular iron-ore and magnetite, with gangue, continues from the surface to a flat system of diabase apophyses occurring at a depth

[4] *Geologiska Föreningen Förhandlingar*, Stockholm, vol. ix., p. 244 (1887).

of from 54 to 60 m., on which the ore spreads like a cake, while below the diabase dikes the rock is dolomite only. In such cases the intrusive dikes have evidently preserved the underlying rock from transformation. A similar instance from Dannemora is mentioned by A. E. Fahlcrantz,[5] who says that over a dike of *hälleflinta* (felsite-porphyry) a band of iron-ore a few inches in thickness was met with, accompanying the *hälleflinta*. In this case, however, it is probable that the ore is a more recent formation; for the majority of the Dannemora ores are certainly older than the felsite-porphyries.

Many limestone beds have been largely, or even wholly, transformed into ores, especially of type D, the gangues of which, consisting of calcium and magnesium silicates, clearly indicate their origin.

At Utö it is questionable whether the concentration of the most prominent ore-deposit is not connected with the two traversing pegmatite dikes. The largest and deepest mines, which have followed the deposit down to a vertical depth of more than 200 m., are situated between these two pegmatite dikes; moreover, on the outer sides of the pegmatites there is a continuous ore-mass, which has been followed down to a comparatively great depth. At some distance from these dikes the ore has everywhere been less thick and less concentrated, and has, therefore, been mined on a small scale only. While the pegmatite dikes evidently originated at a great depth, it follows that the ore-concentration could not have been accomplished earlier than the submersion in the deep-seated zone.

The numerous mines of the Grängesberg, Blötberg, Fredmundsberg, and Gräsberg districts offer good opportunities to observe the relation between the pegmatites and the ores. The former occur here as dikes, partly traversing the ores, and partly parallel to the stratification, but in a manner which indicates that they are of later formation than the ores. Coarsely crystalline magnetite is often found in the pegmatite veins, indicating that the aqueo-igneous solutions giving rise to the pegmatite originated from the same source as the iron-ore.

In this connection attention may be called to the not uncommon fact that the ores of this type occur along contacts, gener-

[5] *Bihang till Handlingar Kongliga Svenska Vetanskaps-Akademie*, Stockholm, 4 (1876).

ally between limestone and granulite, but also along the contact with intrusive rocks. A marked instance of the former mode of occurrence is seen at Persberg (Fig. 6), where the upper ore-bearing horizon occupies a basin with granulite in the foot-wall and dolomized limestone in the hanging-wall. Similar instances

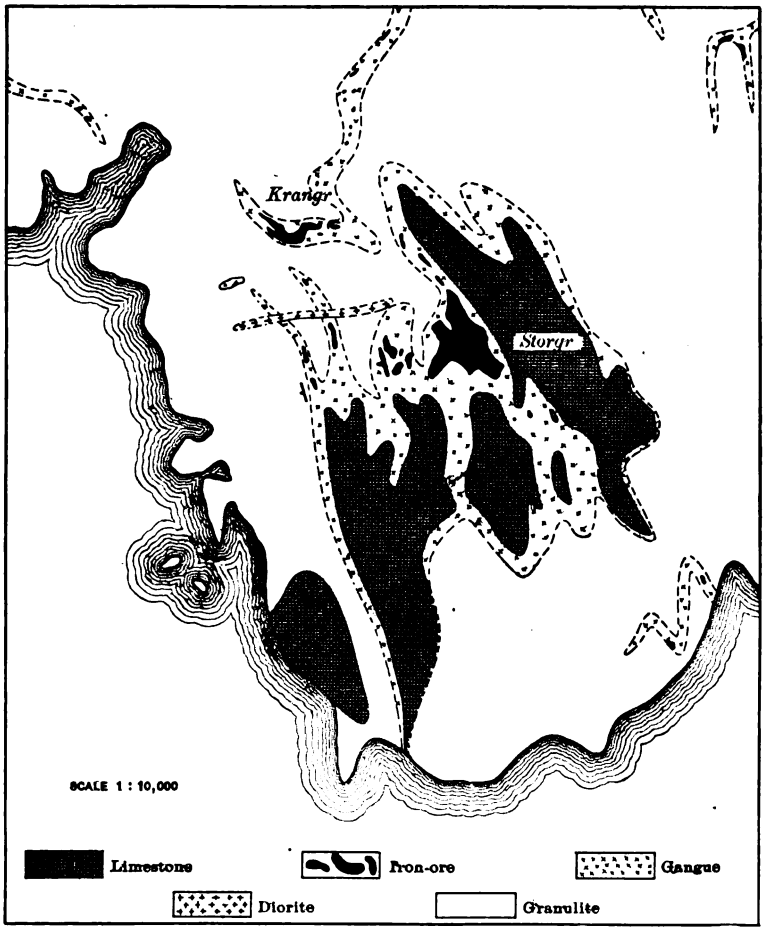

FIG. 6.—PERSBERG.

are found in several other ore-deposits of type D; *e. g.*, the Gåsgrufve mine and the Nordmark mines in Vermland, and Stenring and Ramhäll in Upland. In such cases the situation of the ores along the contact can hardly be explained by assuming them to be of primary origin; the only explanation possible is

that the ores have been precipitated along the contact from ferriferous solutions.

The same explanation presents itself in such a case as that of the Högborn district in Örebro, where the most important deposits occur on a certain level between a diorite mass and the granulite (Fig. 7). If the ores were assumed to have been laid down as a sedimentary deposition on a certain level within the granulite, it would be necessary to explain the fact that the diorite had been injected on this very level and formed a laccolite there. The assumption that the ores are younger than

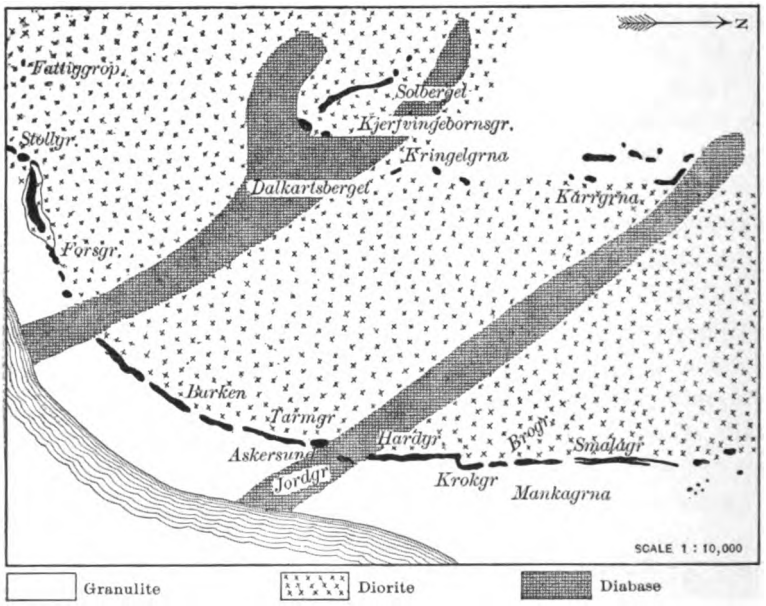

FIG. 7.—HÖGBORN MINES.

the dioritic laccolite, and that they have been precipitated from ferriferous solutions, removes this difficulty. The most satisfactory view, therefore, is that the ores along such contacts are epigenetic formations.

To this period also belongs the formation of the gangues, which are the result of the silicification that takes place in the deep-seated zone. Whole layers of limestone have, through the interchange of constituents, been transformed into lime-magnesia-iron silicates (*skarn*-deposits). If the limestone has already undergone a dolomitizing process, or if Mg is added

by the solution, the chief alteration-products will be amphiboles, which are rich in magnesia; if the limestones are comparatively pure, pyroxenes are formed. Though the garnet of the gangues may often be an alteration-product of pyroxene or amphibole minerals, it may, however, frequently be of primary formation, depending on the chemical composition of the solutions and the transformed material.

Transformations in the Surface-Zone.—When the erosion and removal of the overlying Cambro-Silurian strata exposed the Archæan rocks, the ore-deposits were subjected to the influence of catamorphic agencies.

Among the transformations of this period we have to note the formation of many *skölar* of chlorite and talc (soapstone) by the decomposition of the pyroxene and amphibole of the gangues or the granulite of the wall-rock. Many *skölar*, too, owe their origin to the decomposition of intrusive greenstone veins.

Indeed, the whole mass of the gangues may, under certain circumstances, be changed, quite new ore-types being the result of the transformation. A common phase of this transformation is the occurrence of epidote, quartz, and calcite in the gangue; if the alteration proceeds to a certain degree, hydrated minerals of the talc and chlorite groups are formed. As has been shown by H. V. Tiberg,[6] the gangue in the Taberg mines in Vermland, the ore of which is, in its upper part, markedly talcose, has been formed by metasomatic transformation of augite and amphibole. This transformation reaches only as far down as 320 m., at which depth the ore is cut nearly horizontally by a fissure which yields plenty of water. The same author adduces, also, the Alabama mine in the Persberg district as an instance of similar transformation; in its southern part the ore is talcose, but in the northern part the original gangues, pyroxene and amphibole, are still found. No doubt the ores of Dalkarlsberget, as well as all the ores belonging to the so-called "Rösberg type" of B. Santesson, ought to be interpreted in the same way, as being derived from type D through alteration.

Several other transformations may be viewed as compara-

[6] *Werml. Bergsmannaför. Ann.* (1903).

tively recent and, consequently, belonging to this period. The ores of the Striberg type are often found to lose their characteristic bandedness in the direction of the strike, the quartz being replaced by a somewhat porous magnetite, sometimes also by calcite. Concentrations of richer magnetite often occur among the ores of this type; they are generally accompanied by quartzose segregations or chloritic *skölar*.

Simultaneously with this, a concentration of the iron may take place, SiO_2 being dissolved by means of alkaline carbonates and the silica replaced by ferric oxides. It is by such concentration, for instance, the rich ore deposits have been formed which are often met with in folds; *e. g.*, in Nordmark and in the Högborn mines in Vermland. In localities where very thick deposits of ore not enriched, and retaining the primitive structure, occur in folds, as at the Stripa mine, the abnormal thickness must be ascribed to mechanical deformation.

Among the Gräsberg mines, which are worked on a folded layer in the form of a trough sloping NNW., there occurs in the Bolag mine a highly concentrated magnetite in the fold, the rest of the ore being a poor hematite with quartz bands.[7] That a concentration process has taken place here is beyond doubt, though it is not possible to determine to what period it should be assigned.

On a still larger scale, a similar transformation has taken place in the Bispberg mine, producing a rich, pure magnetite, mined in the deeper levels of this mine, while in the upper parts the ore was a typical low-grade quartz-banded hematite.

Such transformation on a large scale of specular hematite into magnetite has long been known from several ore-deposits; *e. g.*, Norberg, Striberg, Gellivare. In the ends of the ore-bodies and in the sides contiguous to the surrounding rocks the transformation is most advanced, but also the interior portions of the ores consist of a mixture of specular hematite and magnetite. The cause of this transformation is not fully understood; but it is evidently a reaction, depending on mass-action, and continuing to a certain limit, where equilibrium ensues. It looks as if the reaction proceeded from the surrounding or traversing silicate-rocks; and it has been conjec-

[7] H. Sundholm, *Jern-Kontorets Annaler*, vol. liii., p. 162 (1898).

tured that the alteration has been produced by organic substances (humic acids) contained in the surface-waters descending along the walls of these rocks. Even though it might be supposed that these organic substances had the power of reducing specular hematite into magnetite, this explanation is not very satisfactory; for the transformation that has taken place is not a reduction of hematite into magnetite with retention of the structure of the former, but a solution and recrystallization of the iron-ore. One might rather suggest the action of alkaline solutions proceeding from the silicate-rocks, or some other reagent.

The change from hematite to magnetite is reversible; and in some places we meet with transformations on a large scale of magnetite into hematite. Of the anhydrous iron oxides, magnetite is more stable in the deep-seated zone, hematite in the surface-zone; and it seems safe to assume that the last-mentioned alteration belongs to the surface-zone. Such a transformation is found in the Grängesberg mines, where the ore close to the foot-wall consists of a scaly hematite low in phosphorus.

The Grängesberg and Norrbotten Deposits.

A separate position should be assigned to those ores of the type which are chiefly represented by the large deposits of Grängesberg, in central Sweden, and Gellivare, in Norrbotten. They diverge in some points from the majority of the ores of the Archæan schists; and their characteristic properties seem to be most satisfactorily explained by assuming them to be transformed basic segregations in gneiss-granites (orthogneisses).

* * * * * * * * * *

Analogous Deposits.

The ores of this group are well represented within the Archæan series of the United States and Canada; indeed, all the different types mentioned above are found there. This feature, that the same ore-types may be recognized in areas so far apart as North America and the Scandinavian peninsula, strongly indicates that these types correspond to certain genetic conditions.

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[ABRIDGED SUMMARY.—Ores of type A are found at Mineville, Lake Champlain, N. Y., corresponding to the Swedish ores in appearance, composition, form of ore-bodies, etc. Type B, rich in silica and alumina, represents in part the Archæan deposits of New York and New Jersey. Type C recalls at many points the siliceous banded ores of Lake Superior, especially the Archæan ores of the Vermilion range, but also, in some respects, the Huronian ores of Marquette and Crystal Falls. Type D (the "Skarn"-ores) has also its representatives among the Archæan deposits of New York, New Jersey, and Pennsylvania, and in the Cranberry range of North Carolina and Tennessee, and some deposits in Eastern Ontario, Can. The Tilly Foster mine, in Putnam county, N. Y., is a striking instance. Type E seems to be comparatively rare in the United States, but the iron-ore of Franklin, N. J., and some other places in the United States and Ontario, occurs in limestone.

GROUP II.—THE ORES OF THE PORPHYRIES (KERATOPHYRES).

The province of Norrbotten contains many times as much iron as all the rest of Sweden. Some of the deposits in this province may be reckoned among the largest in the world. The export from Kiirunavaara commenced as late as 1902, when the railway to Narvik on the fjord of Ofoten was opened; in the following year the exploitation of the less considerable neighboring deposit of Tuollavaara also began.

Geologically, the iron-ore deposits of Norrbotten are of three kinds: (1) the ores of the crystalline schists, which embrace the deposits of Gellivare and Svappavare, treated in the preceding section; (2) the ores of the Kiiruna type, connected with syenitic porphyries; and (3) ores connected with basic igneous rocks. These ores will be treated in the next section. (See Fig. 8.)

Topographically, the more important deposits may be divided into four groups: (1) Gellivare, embracing Malmberget and Koskulls Kulle and a few copper ore-deposits north of the Lina-elf; (2) Svappavare, Leveäniemi and Mertainen, situated between the Kalix and the Torneå rivers; (3) a group in the vicinity of Lake Luossajärvi, embracing Kiirunavaara, Luossavaara, and Tuollavaara; (4) Ekströmberg, which belongs to the basin of the Kalix river. Besides these, minor deposits, for the most part only imperfectly known, are scattered all over the wide area.

Kiirunavaara, Luossavaara, and Tuollavaara.

The iron-ore deposit of Kiirunavaara is undoubtedly the largest deposit of ore found in Europe. The neighboring deposits of

Luossavaara and Tuollavaara are geologically of the same nature, though smaller. The first two of these deposits have been known for more than two centuries. Luossavaara is mentioned as early as about the year 1690, Kiiruna not before 1736; a description of both is given in the Report of the Government Mining Inspector for 1751. The first survey was made shortly before 1760. Tuollavaara, being concealed under a thick moraine, was not discovered until 1897. (See Fig. 9.)

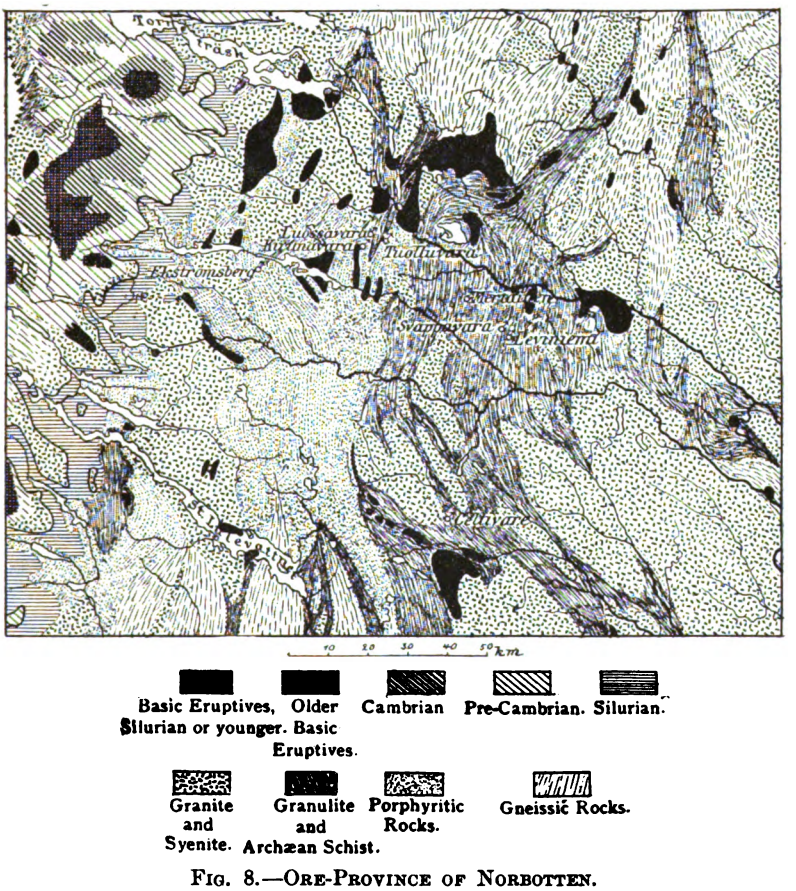

FIG. 8.—ORE-PROVINCE OF NORBOTTEN.

The ores in question prove to be genetically connected with a group of eruptive rocks of syenitic composition, and characterized by their high percentage of soda. These rocks show the structures of deep-seated as well as of vein-rocks. They are intruded in a sedimentary, partly clastic, complex of strata, including conglomerates and semi-crystalline schists.

The porphyritic rocks were, for a long time, regarded by the Swedish geologists, Hummel, Gumælius, Fredholm, and others (in analogy with the case of central Sweden), as a sedimentary *hälleflinta*, and the stratified rock-complex in which they occur was called *hälleflinta*-schist. In 1889, however, Törnebohm pointed out the porphyritic nature of the so-called *hälleflinta*, and afterwards the *hälleflinta*-schists were found to consist of partly clastic rocks.

The ores of the three deposits form stratiform masses of considerably greater length than breadth—the length of the Kiirunavaara deposits is about 2.8 kilometers.

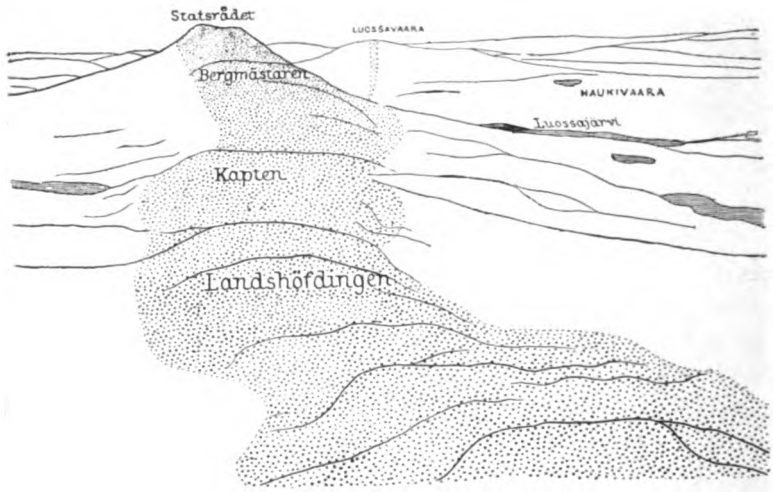

FIG. 9.—PART OF ORE-DEPOSIT OF KIIRUNAVAARA (LOOKING NORTH).

The ores are immediately surrounded by intrusive rocks of porphyritic development which, on account of their composition, are to be referred to the soda-syenite-porphyries. They have also been called keratophyres (H. Bäckström); however, as this name is applied to effusive rocks, and the effusive nature of the Kiiruna porphyries seems to me at least questionable, I prefer, for the present, the name porphyries. Two kinds of porphyry may be distinguished: one more basic, occurring chiefly in the foot-wall, but partly also in the hanging-wall of the ore, and one more acid, often developed as quartz-porphyry and occurring in the hanging-wall of the ores of Kiirunavaara and Luossavaara, around Tuollavaara, etc. The basic porphyry

is closely connected with the syenitic rock which accompanies it.

The Syenite.—This is a soda-syenite, the chief mass of which is a soda-feldspar. Secondary basic minerals are present in abundance. The structure is eugranitic. This soda-syenite shows gradations into the porphyry of the foot-wall, with which it is closely allied in composition.

The Porphyry of the Foot-Wall.—This rock presents, microscopically as well as macroscopically, a fluidic structure with a trachytoidal arrangement of the feldspar of the ground-mass; sometimes, also, spherulitic structures are observable. The primary structures are, however, frequently difficult to distinguish, being in part totally obliterated by the alteration of the rock. The basic constituents are almost wholly altered into amphibole, epidote, and chlorite. Magnetite seems to occur in two generations: one primary, the other of later immigration. As fissure-minerals, indicating a secondary action of pneumatolytic nature, occur amphibole, titanite, apatite, and magnetite. In the contact-zone the fissures sometimes form cavities a decimeter in diameter, filled with the said mineral combination.

The Porphyry of the Hanging-Wall.—This is considerably more acid (containing 10 per cent. more of SiO_2) than the syenite and the porphyry of the foot-wall, which circumstance places it among the quartz-porphyries. Quartz occurs in the ground-mass partly as so-called "*quartz globulaire*," but in larger quantities where the ground-mass has undergone a recrystallization. Here, too, a secondary generation of magnetite can be observed. The primary basic mineral constituents are completely altered, having produced amphibole, epidote, and chlorite. The rock shows, even macroscopically, a distinct fluidic structure.

Segregations of pure magnetite, mostly in rounded pieces, are worthy of notice; these segregations sometimes show a concentric structure and at times inclose grains of the feldspar of the porphyry. When the fragmentary character is more distinct, they are probably portions of segregations, solidified in depth at an earlier date, which have been partly rounded by resorption. These segregations have also been interpreted as fragments of the great ore-body; and from this it has been concluded that the porphyry of the hanging-wall should be younger than the mass of ore.

The unmistakable "consanguinity" between the soda-syenite and the porphyries is manifested by the high percentage of Na, which varies between 5.5 and 7.5 per cent.; apatite, titanite, and magnetite are, besides, minerals common to the syenite, the porphyries, and the ore-deposits.

The Ores.—(In the following exposition of the Kiirunavaara and Luossavaara ore-deposits, I follow chiefly the official report made by Hj. Lundbohm in 1898.) The iron-ore occurring among the porphyry masses forms, on the whole, pure, nearly homogeneous ore-deposits; other minerals found in it are of comparatively subordinate significance.

A property characteristic of the ore of Kiiruna-, Luossa-, and Tuollavaara is its general extremely fine-grained texture, which proves that it has been subject to a slight degree only to the action of recrystallizing agents. By this structure, which is also found in a few other ores in Norbotten, this ore-type is distinguished from the rest of the Scandinavian ores.

The only mineral that occurs in the ore with undoubtedly primary characters is apatite, the distribution of which is exceedingly irregular, so that the percentage of phosphorus in the ore varies greatly.

In Kiirunavaara, chiefly close to the foot-wall, but also here and there in the interior of the ore, occurs an ore-type with mostly grayish-black and dull, compact fracture (Lundbohm's type 5). When examined with the microscope it proves to be interlarded with apatite individuals idiomorphically developed; its phosphorus-percentage is from 3 to 6 per cent. This ore frequently presents a stratiform structure.

The ore-type which quantitatively predominates contains the apatite in nodules and irregular lenses (Lundbohm's type 4). Here, too, the apatite seems to be, at least in part, of primary origin, since it occurs partly as a minute impregnation of the ore, partly in irregular nests and veins, giving rise to a structure which bears some resemblance to a largely developed flow-structure (Fig. 10).

Primary structural forms which may be referred to flow-structure may also be observed in the relations between different ore-types, when, *e.g.*, one type contains fragments or "*schlieren*" of another type, or when one ore-type occurs as intruding dikes in another (Fig. 11). Especially on weathered ore-surfaces these structures are easily observable.

It is likely that the highly phosphoric ores, though embracing several types, must in general be regarded as primary, and those poorer in apatite as secondary, leached, and in part recrystallized. The latter also contain martite and specular hematite, the occurrence of which is here evidently secondary.

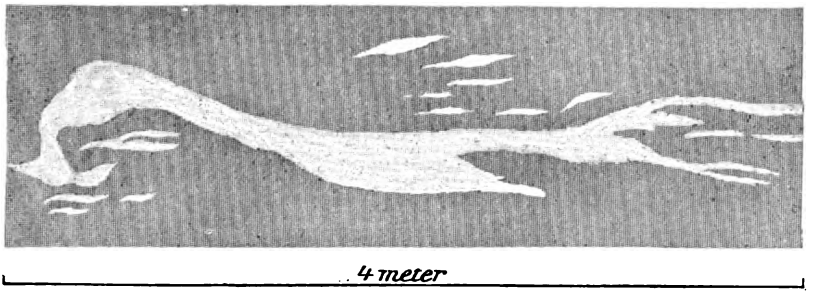

FIG. 10.—IRREGULAR VEINS OF APATITE IN MAGNETITE, KIIRUNAVAARA (Lundbohm).

In the low-phosphorus ores occur also calcite (formed at the expense of the apatite), secondary quartz in fissures, and secondary silicates as amphibole, talc, and chlorite minerals. The secondary ore-types are sometimes porous, the more soluble minerals having been leached out.

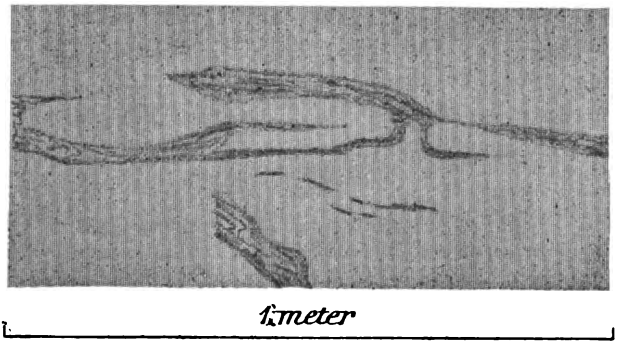

FIG. 11.—FLOW-STRUCTURE IN MAGNETITE, KIIRUNAVAARA (Lundbohm).

From a practical point of view, the ores in question have been divided into several classes according to their percentage of phosphorus. Those classes which range above 1 per cent. constitute the principal mass of the ores of Kiirunavaara. As a fairly certain result of the examinations of the ores with regard to their percentage of phosphorus, it may be said that ores con-

taining less than 0.05 per cent., and ores with from 0.05 to 0.1 per cent., of phosphorus, occur separately in such a mode that they can be utilized, but that both kinds, especially the former, are, as regards quantity, rather subordinate to those richer in phosphorus.

* * * * * * * * * *

The Genesis of the Deposits.—The genetic connection of these ores with the porphyry-rocks is so manifest, that it has been admitted by all who have expressed their opinion on the subject. Even those geologists (Hummel and Gumælius in 1875, Fredholm in 1891), who regarded the porphyries as sedimentary *hälleflintor*, acknowledged this connection, and consequently considered the ores as sedimentary formations. Löfstrand, in 1891 and 1892, in describing other basic segregations and vein-like formations of iron-ore in acid igneous rocks, pointed out that the connection of the ores of Kiiruna with the porphyries ought to be interpreted in the same way. The same opinion was expressed more positively in 1898 by Högbom,[17] who laid special stress on the agreement with the deposits connected with syenitic rocks in the eastern Ural: Wyssokaia Gora, Lebiajaia, and Gora Blagodat. A similar opinion was pronounced at a later time by O. Stutzer, who holds that the ores have been formed in an epigenetic-magmatic way as "eine nach oben gewanderte magmatische Ausscheidung"—*i. e.*, a magmatic vein-formation.

A pneumatolytic sedimentary mode of formation has been maintained by Bäckström and, later, by De Launay (1903). The latter author, who gives the most detailed exposition of this view, has formed the following conception of the process: The porphyry of the foot-wall is an effusive rock, on which the iron-ore, formed through the decomposition of chloride and sulphide of iron in contact with water, has been deposited. Later on a new eruption of porphyry followed, by which the porphyry of the hanging-wall was formed.

This interpretation is based on the opinion that the ore is younger than the porphyry of the foot-wall and older than the porphyry of the hanging-wall, which, however, is hardly com-

[17] *Geologiska Föreningen Förhandlingar*, Stockholm, vol. xx., p. 115 (1898).

patible with the fact that the magnetite is, in places completely surrounded by the basic porphyry.

The above-mentioned fluidic structures in the magnetite can be accounted for only by assuming that the magnetite, together with the greater part of the apatite, has formed a segregation from an iron-alkali-silicate magma, intruded as a vein between the porphyries. After this intrusion the effects of pneumatolytic agencies, which are especially well-marked at the contact with the basic porphyry, have arisen. Högbom has given a theoretical exposition of the formation of ores of this kind. He starts from an iron-alkali-silicate magma composed, approximately, in the proportion of 1 molecule of orthoclase, 1 molecule of albite, and 1 molecule of magnetite. Such a magma differs in composition from known and common magma-types only by containing a little more ferric oxide and a somewhat smaller amount of lime and magnesia. As, at the solidification of such a magma, the larger part of the iron must segregate as magnetite, because, owing to the absence of lime and magnesia, it cannot combine with the silica, the differentiation of two rocks, one chiefly consisting of magnetite, the other of feldspar, is easily accounted for. Högbom, therefore, holds that the alkali-silicate magmas rich in iron, to which petrography has as yet paid but little attention, have a just claim to a place in the system, and that their most typical representatives are magnetite-bearing syenitic rocks of this kind.

* * * * * * * * * *

[Abridged Summary.—At Mertainen, 30 km. southeast of Kiiruna, the ores are connected with a syenite-porphyry, mainly consisting of a soda-feldspar. At the contact, the rock has undergone pneumatolytic transformation. Its original basic constituents have disappeared and new magnesia silicates appear in their place. The soda-feldspar has, in part, been transformed into scapolite, but biotite and titanite also have been produced. The magnetite occurs partly finely disseminated, partly in small segregations, from the size of an almond to that of an egg. These have been interpreted as cavity-fillings; but the deposit is properly a magnetite breccia. A fine-grained magnetite fills the corrosion-fissures of the rock, associated sometimes with amphibole, less frequently with apatite. A similar deposit occurs at Painirova, 8 miles to the south. The deposits of Mertainen and Painirova are, like those of Kiiruna, genetically connected with the syenite-porphyries. But at Mertainen the pneumatolytic characters are most marked, and there is nothing like the pure ore-masses of magmatic origin and partly of fluidic structure which form the main deposit at Kiiruna. At Ekströmberg, about 30 km. west of Kiirunavaara, the ore is connected with syenitic porphyries; and many other deposits of this general class are known in Norrbotten.]

Analogous Deposits.

The ores in Norrbotten of the Kiiruna type belong to a particularly well-defined geological-petrographical type, which is also met with in other parts of the world.

Högbom has already, in the above-mentioned paper, pointed out the agreement between the iron-ore deposits in the eastern Ural and the Kiiruna type. In the iron-mountains of the Ural a secondary epidotization of the rocks has taken place on a larger scale than in Norbotten, especially along certain planes of dislocation. On the other hand, the pneumatolytic characters so well marked in the Kiiruna type are not met with in the deposits of the Ural. The secondary transformations, such as the development of martite and specular hematite, the leaching out of pyrite and apatite, the formation of porous ore or ore containing calcite, and the accumulation of the apatite chiefly near the foot-wall, are common to the two districts.

The ores of the (for the most part exhausted) deposits of Iron Mountain and Pilot Knob in Missouri, which also occur in association with porphyry-rocks, have been compared to and classed with the Kiiruna type by several authors. At Iron Mountain the ore mined occurred as veins and irregular masses of martite and specular iron-ore in a mostly decomposed porphyry of Archæan age. At Shepherd Mountain similar deposits in porphyry were worked. The deposits of Pilot Knob, on the contrary, are secondary redepositions of the primary iron of the porphyry; they seem to bear a strong resemblance to the deposit of specular iron-ore in the Hauki schists east of Luossavaara.

Also, the Mexican deposits at Durango and Las Truchas agree in some respects with those in Norbotten; but their geological conditions have not, as yet, been sufficiently investigated to make a direct comparison possible.

Group III.—Iron-Ores Formed by Magmatic Segregation in Basic Eruptives.

The ores of this kind form a natural and well-defined class encountered in all parts of the world. That they are genetically connected with eruptive rocks has long been admitted. The nature of their facies of differentiation was not understood

until the differentiation of rock-magmas was clearly conceived. In this regard, their structural characters, which are the same as those of the eruptive rocks, and their frequent presentation of all degrees of transition to the normal rock, are evidential. (Fig. 13.)

Magmatic differentiations of this kind seem to be connected only with intrusive eruptives, and occur in laccolites as well as in vein-like intrusions. In general, a distinction can be made between such differentiations as have taken place within the mass of the laccolite, *in situ*, and such as have taken place in the deep-seated magma. In the latter case the product of magmatic segregation has been carried up to the level of the laccolite by a separate act of eruption.

Taberg in Småland.

As far as a hundred years back Hausmann[18] expressed the opinion that "the mass of Taberg is a greenstone bed of tolerably great thickness, mixed with much iron-ore and lying in gneiss." Through the investigations of A. Sjögren[19] and Törnebohm[20] it was established that the ore-deposit of Taberg ought to be considered as a segregation in a basic eruptive, the chief constituents of which are olivine, plagioclase, a rhombic pyroxene, and magnetite. The structure is that of a deep-seated rock, and the rock, which has been called hyperite by the Swedish geologists, is olivine-norite according to the nomenclature of Rosenbusch. Taberg was the first iron-ore deposit interpreted as a phase of an eruptive rock. Törnebohm[21] says that the Taberg ore "may be regarded as a variety of hyperite rich in iron." As the ideas of magnetic differentiation were not clearly formulated until later, the nature of the ore could not in 1881 be expressed in plainer terms. The whole of the eruptive constitutes an intrusion (laccolite) in the surrounding gneiss, above which it now rises, by reason of its greater power of resistance to erosion. (Fig. 14.)

The ore-deposit occupies the central portion of the mountain. The ore-segregation consists of titaniferous magnetite and

[18] *Reise durch Skandinavien*, Pt. I., pp. 158 to 167 (1806–07).

[19] *Geologiska Föreningen Förhandlingar*, vol. iii., p. 42 (1876).

[20] *Idem*, vol. v., p. 610 (1881).

[21] *Loc. cit.*

FIG. 13.—DISTRIBUTION OF TITANIFEROUS IRON-ORES.

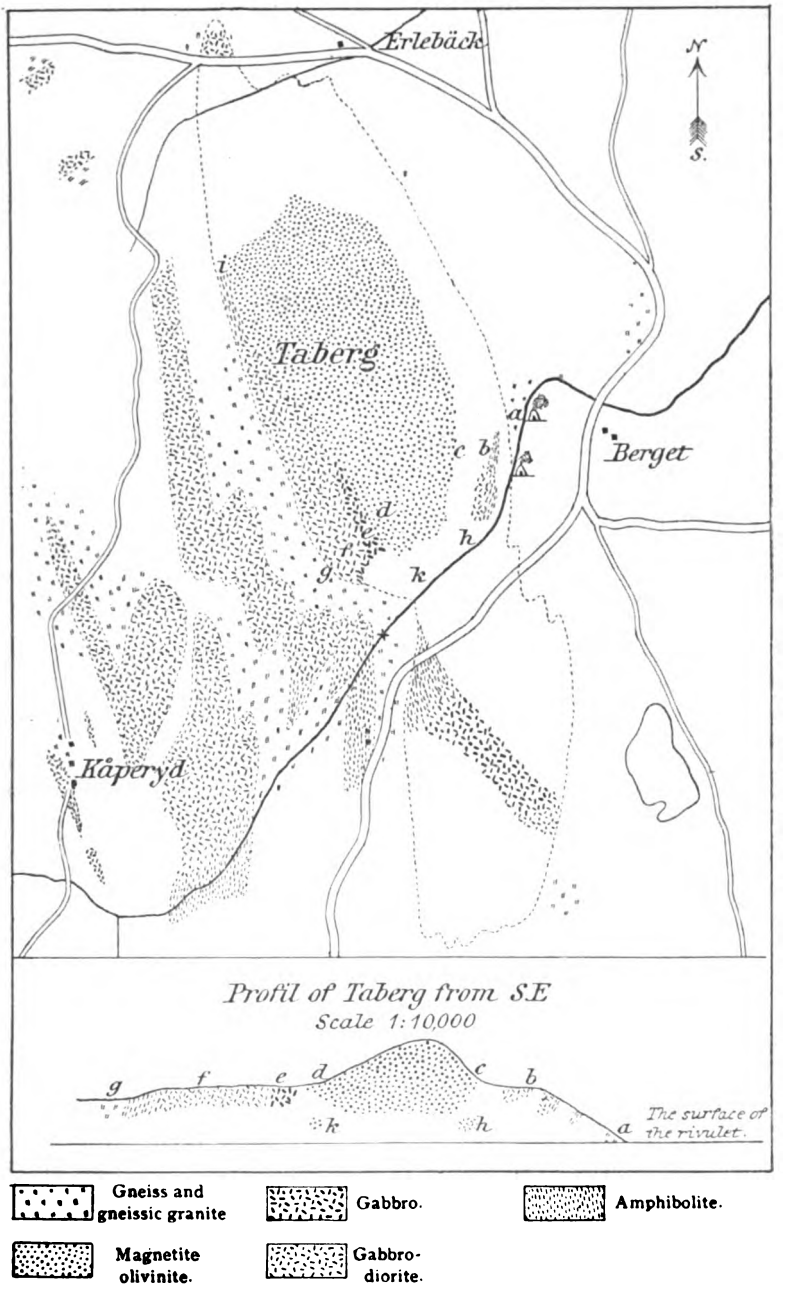

FIG. 14.—TABERG (Törnebohm).

olivine and has received the petrographical name magnetite-olivinite. Where it approaches the normal rock, it first takes up plagioclase, then pyroxene, so that there is a transition from the ore to the normal rock, which also contains magnetite and olivine. The ore-stock thus forming the kernel of the mountain is next surrounded by a shell or mantle of normal gabbro, which, in its turn, towards the inclosing gneiss, passes into the schistose, dynamo-metamorphic border-facies, the gabbro-amphibolite.

The ore is poor throughout, carrying generally from 20 to 30 per cent. of iron. Vein-like segregations containing up to 60 per cent. occur as rare exceptions. Titanic acid varies between 4 and 6 per cent.; the percentage of phosphorus does not exceed 0.1; to which may be added a constant percentage of vanadine.

* * * * * * * * * *

[ABRIDGED SUMMARY.—Minor deposits in central and southern Sweden, and several in Norway, belong to this class. And in the small islands along the coast of Angumanland occur similar segregations in a diabase younger than the Dala sandstone, forming, between stratified quartzites, bed-like intrusions which have been exposed by erosion. The darker bands of this rock have acquired, in some places, through a concentration of titano-magnetite, the character of iron-ore. The proportion of titanic acid may amount to 25 per cent. In the island of Alnö concentrations of titano-magnetite in a boss of nepheline-syenite have been worked in a small way as iron-mines. At Ekersund and Soggendal, in Norway, deposits of iron-ore occur in a colossal laccolite of highly differentiated basic rocks, supposed to be of post-Silurian age. They have been worked at different times, but without commercial profit, since they contain, as an average, only 40 per cent. of iron, and from 40 to 42 per cent. of titanic acid. Deposits of this class are numerous along the coast of Norway, in laccolites laid bare by the fjords. One of the largest in Scandinavia is that of Routivare in Norrbotten, which was formed by segregations in an intrusive rock, occurring as a laccolite in the metamorphic Silurian formations.]

Summary.

Though the rocks which inclose the deposits of this class differ in composition (as real gabbros, norites, diabases, or nepheline-syenites), as well as in age (some of them belonging to the oldest Archæan formation, and the youngest dating from post-Silurian time), yet a marked degree of basicity seems to be a necessary condition for the formation of such concentrations. Vogt puts the highest acidity at 57 per cent. of SiO_2. The majority of the deposits occur in rocks with a silica-percentage of from 48 to 54 per cent. The different facies of gabbro-rocks inclose deposits of different character. The pure

ilmenite-segregations (Ekersund, Soggendal, Lofoten, etc.), seem to be confined to the labradoritic rock. In the same rock-series we also find the ilmenite-norite. In the olivine-gabbro, rich in magnesia, which incloses the deposit of Taberg, the segregation has assumed the mineralogical character of magnetite-olivinite, and in the rocks which are richer in alumina, magnetite-spinellite has been segregated, as at Routivare, Andopen, on Stjernö in Finnmarken, and elsewhere.

A remarkable feature of the ore-concentrations in question is their occurrence, almost without exception, in the central parts of the eruptive masses. This gives them a character different from that of those concentrations of basic constituents in an eruptive rock which are often met with along the margins of rock-veins, and in which the enrichment has not proceeded so far as to form an iron-ore.

As to the degree of concentration of the iron, the ore-types differ also from one another. The concentrates richest in iron are the magnetite-spinellites, with an iron-percentage exceeding 50 per cent. (Routivare, 50 to 54; Solnör, 54; Hellevig, 51; Andopen, nearly 60). Next to these come the segregations of the nepheline-syenites, of which in Alnö some contain from 46 to 53 per cent.; and after these the ilmenite-segregations in the labradoritic rock and the norite, with about 40 per cent. of iron, and nearly as high a percentage of titanic acid. Poorer still are the ores of the olivine-gabbros of the Taberg type, which contain little more than 30 per cent. of iron. Comparable to them are the ores of the olivine-diabase (the Ulfö type), with about 34 per cent. At the bottom of the scale stands the ilmenite-norite, the Storgång type, with about 21 per cent. of iron.

Besides the iron, it is chiefly the titanic acid, the magnesia, and the alumina that have been concentrated. The percentage of titanic acid is highest in the ilmenite-segregations of the labradorite and norite, where it amounts to from 39 to 43 per cent.; next come the ilmenite-norites, which contain 18 per cent.; the magnetite-spinellites (type Routivare) vary between 10 and 18 per cent.; the segregations of the nepheline-syenite show about 10 per cent. (the Trygg mine, in Alnö, from 9.10 to 12.14); in the Taberg type, the magnetite-olivinite, the percentage of titanium, like that of iron, is the lowest—viz., 6.30

in the Taberg ore and 8.50 in the ore of Långhult. The Ulfö type, with about 10 per cent. of TiO_2, shows the greatest agreement with the Taberg type.

The concentration of magnesia has taken place not so much in the ore as in the concentration-facies between the normal rock and the segregations richest in iron. It manifests itself in the formation of Mg-Fe silicates of the olivine and pyroxene groups. The rock-facies, which have received the names magnetite-olivinite, ilmenite-norite, and ilmenite-enstatite, have originated in this way. A certain percentage of Mg is found even in the purest segregations of ilmenite in the labradoritic rock, owing to a mixture with $MgTiO_2$. The alumina left in the final concentrates combines particularly with the magnesia, thus forming spinel, the formation of which is favored by the relation-deficiency of silica in the magma. This mineral occurs in the following ore-types: the magnetite-olivinite (Ransberg); the ilmenite-norite (Ekersund); and the magnetite-spinellite (Routivare, Hellevig, Lofoten, and Stjernö). Vogt has called attention to the fact that the Mg-percentage increases in the first stage of concentration and then diminishes. While the original magma contains more Al_2O_3 than MgO, the case is quite the reverse in the earlier stages of concentration. In the final product, however, the amount of alumina again exceeds that of magnesia.

Besides the aforesaid substances, chrome and vanadium, which occur in small quantities, have undergone a concentration. The phosphorus, on the other hand, is not in general concentrated to any noteworthy degree. To this, however, there are exceptions, such as the segregations of ilmenite-norite traversing the labradoritic rock in the Soggendal-Ekersund field, which contain a fairly high percentage of phosphorus, while the surrounding rock carries little, and the above-mentioned concentrations, rich in apatite, in the hypersthene-gabbro at Krekling, Norway, and also in the nepheline-syenite of Alnö.

That silica, lime, and alkalies occur in smaller quantities in the concentrates than in the rest of the rock-mass is manifested mineralogically by the total absence of feldspar from these concentrations.

Vogt has pointed out[22] that in several places in Lofoten and Vesteraalen, in the labradoritic rock containing olivine and hypersthene, there are besides segregations of magnetite-dialagite, also *schlieren*-like segregations of pure olivine rock as well as of hypersthenite. This shows that in the same magma differentiation processes following different lines have taken place nearly contemporaneously. As extreme basic segregations the limestones occurring in the nepheline-syenite may also be explained.

Many different attempts to suggest the cause of these differentiations have been made, but no satisfactory explanation has as yet been proposed.[23] It seems as if, with respect to this kind of segregations, the view according to which the magma is regarded as a mixture of different liquids, partly insoluble in one another, were decidedly preferable to the theory which considers the laws of dilute solutions applicable to the magma. The principle of limited solubility must be considered as the physico-chemical principle governing the differentiation-phenomena of silicate-magmas in general.

Neither "Soret's principle," nor any other form of the theory of diffusion, nor "connection currents," nor the magnetic attraction of the "liquid molecules," nor the different weight of the segregated solid constituents can afford an explanation of differentiation-phenomena of this kind. The geological conditions also seem to harmonize better with the view which connects the differentiation with the segregation and solidification of liquids insoluble in the remaining magma. These are separated out in consequence of the cooling of the magma, by which the conditions of solubility are changed, or of the escape of water or other mineralizers; the segregation takes place at first in the form of drops throughout the magma, which drops, on account of the surface-tension, have a decided tendency to coalesce and flow together into *schlieren* and larger concentrations. Which of the liquids is attracted to the side-walls and solidifies there, and which of them solidifies in the center, will in each case depend on the relative force of the adhesion to the side-walls.

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[22] *Zeitschrift für praktische Geologie*, vol. xiv., pp. 217 to 233 (1906).

[23] Vogt, *Zeitschrift für praktische Geologie*, vol. ix., pp. 327 to 340 (1901).

Analogous Deposits.

Titaniferous iron-ore segregations in basic eruptive masses constitute a well-defined class, which has representatives in all parts of the world. Several of the different types found in Scandinavia occur in other countries also.

In the United States and Canada these ores have long been grouped together as a separate class, and a great many deposits of this kind have been described.

The magnetite-olivinite or Taberg type is analogous to the deposit at Iron-mine Hill in Cumberland, R. I., described by Wadsworth, though the latter is of smaller dimension. The "gabbro titanic-iron-ores" of the Mesabi range in Minnesota, described by N. H. and H. V. Winchell, also seem to come very near to the type, though the concentration of the iron and the titanium has in these ores proceeded further. Among the segregations occurring in large masses in the various gabbro and labradoritic rocks of the eastern Adirondacks, the Taberg as well as the Ekersund type is represented.

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[24] "The Iron-Ore and Emery in the Cortlandt Norite," in Norites of the "Cortlandt Series," on the Hudson River near Peekskill, N. Y., *American Journal of Science*, Third Series, vol. xxxiii., No. 195, p. 194 (Mar., 1887).

[25] H. S. Washington. Igneous Complex of Magnet Cove, Arkansas, *Bulletin of the Geological Society of America*, vol. xi., pp. 389 to 416 (1900).

Utilization.

From the above it appears that the Scandinavian countries inclose very large supplies of iron-ores of this kind, and that, in reality, some of these deposits, such as Taberg, Routivare, Ekersund-Soggendal, etc., are among the largest iron-ore deposits in Sweden and Norway. Numerous attempts at exploiting them have been made in different parts of the two countries. Taberg has given rise to a local iron industry on a small scale carried on during two centuries. The ores of Ulfö have been used in several blast-furnaces in Norrland; from Ekersund-Soggendal during a succession of years ore was exported to England and smelted there; numerous minor mines scattered all over Sweden and Norway bear testimony to the attention which these deposits have attracted. However, all these attempts have been given up because of the unfitness of the ores for metallurgical purposes, which is also the cause why all or nearly all other titaniferous iron-ores all over the world lie unworked.

GROUP IV.—THE IRON-ORES OF THE METAMORPHOSED CAMBRO-SILURIAN SCHISTS.

These ores, which form a very well-defined geological class, are also territorially confined to a certain "ore-province." They occur exclusively within the area of more or less metamorphosed schists which forms the greater part of the mountain-districts of the Scandinavian peninsula north of the 65th degree of latitude. Through the abrasion of the Atlantic and the erosion the ore-bearing horizons have in places been laid bare; these ores are therefore almost exclusively confined to the Norwegian coast and the valleys penetrating into the country from the sea. The fjord-valleys deeply indenting the coast, as well as the nearest islands, are rich in deposits of this kind.

These ores have long been known, but, in spite of the favorable situation of several of the larger deposits on or near the Atlantic, they have been exploited, either not at all or to very small extent, by reason of their low percentage of iron. Only since the introduction of magnetic ore-concentration have attempts been made to utilize them for export on a larger scale.

[A discussion of the geological horizon of this group, and descriptions of Dunderland, Naeverhaugen, Salangen, etc., follow.]

taining less than 0.05 per cent., and ores with from 0.05 to 0.1 per cent., of phosphorus, occur separately in such a mode that they can be utilized, but that both kinds, especially the former, are, as regards quantity, rather subordinate to those richer in phosphorus.

* * * * * * * * * *

The Genesis of the Deposits.—The genetic connection of these ores with the porphyry-rocks is so manifest, that it has been admitted by all who have expressed their opinion on the subject. Even those geologists (Hummel and Gumælius in 1875, Fredholm in 1891), who regarded the porphyries as sedimentary *hälleflintor*, acknowledged this connection, and consequently considered the ores as sedimentary formations. Löfstrand, in 1891 and 1892, in describing other basic segregations and vein-like formations of iron-ore in acid igneous rocks, pointed out that the connection of the ores of Kiiruna with the porphyries ought to be interpreted in the same way. The same opinion was expressed more positively in 1898 by Högbom,[17] who laid special stress on the agreement with the deposits connected with syenitic rocks in the eastern Ural: Wyssokaia Gora, Lebiajaia, and Gora Blagodat. A similar opinion was pronounced at a later time by O. Stutzer, who holds that the ores have been formed in an epigenetic-magmatic way as "eine nach oben gewanderte magmatische Ausscheidung"—*i. e.*, a magmatic vein-formation.

A pneumatolytic sedimentary mode of formation has been maintained by Bäckström and, later, by De Launay (1903). The latter author, who gives the most detailed exposition of this view, has formed the following conception of the process: The porphyry of the foot-wall is an effusive rock, on which the iron-ore, formed through the decomposition of chloride and sulphide of iron in contact with water, has been deposited. Later on a new eruption of porphyry followed, by which the porphyry of the hanging-wall was formed.

This interpretation is based on the opinion that the ore is younger than the porphyry of the foot-wall and older than the porphyry of the hanging-wall, which, however, is hardly com-

[17] *Geologiska Föreningen Förhandlingar*, Stockholm, vol. xx., p. 115 (1898).

patible with the fact that the magnetite is, in places completely surrounded by the basic porphyry.

The above-mentioned fluidic structures in the magnetite can be accounted for only by assuming that the magnetite, together with the greater part of the apatite, has formed a segregation from an iron-alkali-silicate magma, intruded as a vein between the porphyries. After this intrusion the effects of pneumatolytic agencies, which are especially well-marked at the contact with the basic porphyry, have arisen. Högbom has given a theoretical exposition of the formation of ores of this kind. He starts from an iron-alkali-silicate magma composed, approximately, in the proportion of 1 molecule of orthoclase, 1 molecule of albite, and 1 molecule of magnetite. Such a magma differs in composition from known and common magma-types only by containing a little more ferric oxide and a somewhat smaller amount of lime and magnesia. As, at the solidification of such a magma, the larger part of the iron must segregate as magnetite, because, owing to the absence of lime and magnesia, it cannot combine with the silica, the differentiation of two rocks, one chiefly consisting of magnetite, the other of feldspar, is easily accounted for. Högbom, therefore, holds that the alkali-silicate magmas rich in iron, to which petrography has as yet paid but little attention, have a just claim to a place in the system, and that their most typical representatives are magnetite-bearing syenitic rocks of this kind.

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[Abridged Summary.—At Mertainen, 30 km. southeast of Kiiruna, the ores are connected with a syenite-porphyry, mainly consisting of a soda-feldspar. At the contact, the rock has undergone pneumatolytic transformation. Its original basic constituents have disappeared and new magnesia silicates appear in their place. The soda-feldspar has, in part, been transformed into scapolite, but biotite and titanite also have been produced. The magnetite occurs partly finely disseminated, partly in small segregations, from the size of an almond to that of an egg. These have been interpreted as cavity-fillings; but the deposit is properly a magnetite breccia. A fine-grained magnetite fills the corrosion-fissures of the rock, associated sometimes with amphibole, less frequently with apatite. A similar deposit occurs at Painirova, 8 miles to the south. The deposits of Mertainen and Painirova are, like those of Kiiruna, genetically connected with the syenite-porphyries. But at Mertainen the pneumatolytic characters are most marked, and there is nothing like the pure ore-masses of magmatic origin and partly of fluidic structure which form the main deposit at Kiiruna. At Ekströmberg, about 30 km. west of Kiirunavaara, the ore is connected with syenitic porphyries; and many other deposits of this general class are known in Norrbotten.]

Analogous Deposits.

The ores in Norrbotten of the Kiiruna type belong to a particularly well-defined geological-petrographical type, which is also met with in other parts of the world.

Högbom has already, in the above-mentioned paper, pointed out the agreement between the iron-ore deposits in the eastern Ural and the Kiiruna type. In the iron-mountains of the Ural a secondary epidotization of the rocks has taken place on a larger scale than in Norbotten, especially along certain planes of dislocation. On the other hand, the pneumatolytic characters so well marked in the Kiiruna type are not met with in the deposits of the Ural. The secondary transformations, such as the development of martite and specular hematite, the leaching out of pyrite and apatite, the formation of porous ore or ore containing calcite, and the accumulation of the apatite chiefly near the foot-wall, are common to the two districts.

The ores of the (for the most part exhausted) deposits of Iron Mountain and Pilot Knob in Missouri, which also occur in association with porphyry-rocks, have been compared to and classed with the Kiiruna type by several authors. At Iron Mountain the ore mined occurred as veins and irregular masses of martite and specular iron-ore in a mostly decomposed porphyry of Archæan age. At Shepherd Mountain similar deposits in porphyry were worked. The deposits of Pilot Knob, on the contrary, are secondary redepositions of the primary iron of the porphyry; they seem to bear a strong resemblance to the deposit of specular iron-ore in the Hauki schists east of Luossavaara.

Also, the Mexican deposits at Durango and Las Truchas agree in some respects with those in Norbotten; but their geological conditions have not, as yet, been sufficiently investigated to make a direct comparison possible.

Group III.—Iron-Ores Formed by Magmatic Segregation in Basic Eruptives.

The ores of this kind form a natural and well-defined class encountered in all parts of the world. That they are genetically connected with eruptive rocks has long been admitted. The nature of their facies of differentiation was not understood

until the differentiation of rock-magmas was clearly conceived. In this regard, their structural characters, which are the same as those of the eruptive rocks, and their frequent presentation of all degrees of transition to the normal rock, are evidential. (Fig. 13.)

Magmatic differentiations of this kind seem to be connected only with intrusive eruptives, and occur in laccolites as well as in vein-like intrusions. In general, a distinction can be made between such differentiations as have taken place within the mass of the laccolite, *in situ*, and such as have taken place in the deep-seated magma. In the latter case the product of magmatic segregation has been carried up to the level of the laccolite by a separate act of eruption.

Taberg in Smdland.

As far as a hundred years back Hausmann [18] expressed the opinion that "the mass of Taberg is a greenstone bed of tolerably great thickness, mixed with much iron-ore and lying in gneiss." Through the investigations of A. Sjögren [19] and Törnebohm [20] it was established that the ore-deposit of Taberg ought to be considered as a segregation in a basic eruptive, the chief constituents of which are olivine, plagioclase, a rhombic pyroxene, and magnetite. The structure is that of a deep-seated rock, and the rock, which has been called hyperite by the Swedish geologists, is olivine-norite according to the nomenclature of Rosenbusch. Taberg was the first iron-ore deposit interpreted as a phase of an eruptive rock. Törnebohm [21] says that the Taberg ore "may be regarded as a variety of hyperite rich in iron." As the ideas of magnetic differentiation were not clearly formulated until later, the nature of the ore could not in 1881 be expressed in plainer terms. The whole of the eruptive constitutes an intrusion (laccolite) in the surrounding gneiss, above which it now rises, by reason of its greater power of resistance to erosion. (Fig. 14.)

The ore-deposit occupies the central portion of the mountain. The ore-segregation consists of titaniferous magnetite and

[18] *Reise durch Skandinavien*, Pt. I., pp. 158 to 167 (1806–07).

[19] *Geologiska Föreningen Förhandlingar*, vol. iii., p. 42 (1876).

[20] *Idem*, vol. v., p. 610 (1881).

[21] *Loc. cit.*

FIG. 13.—DISTRIBUTION OF TITANIFEROUS IRON-ORES.

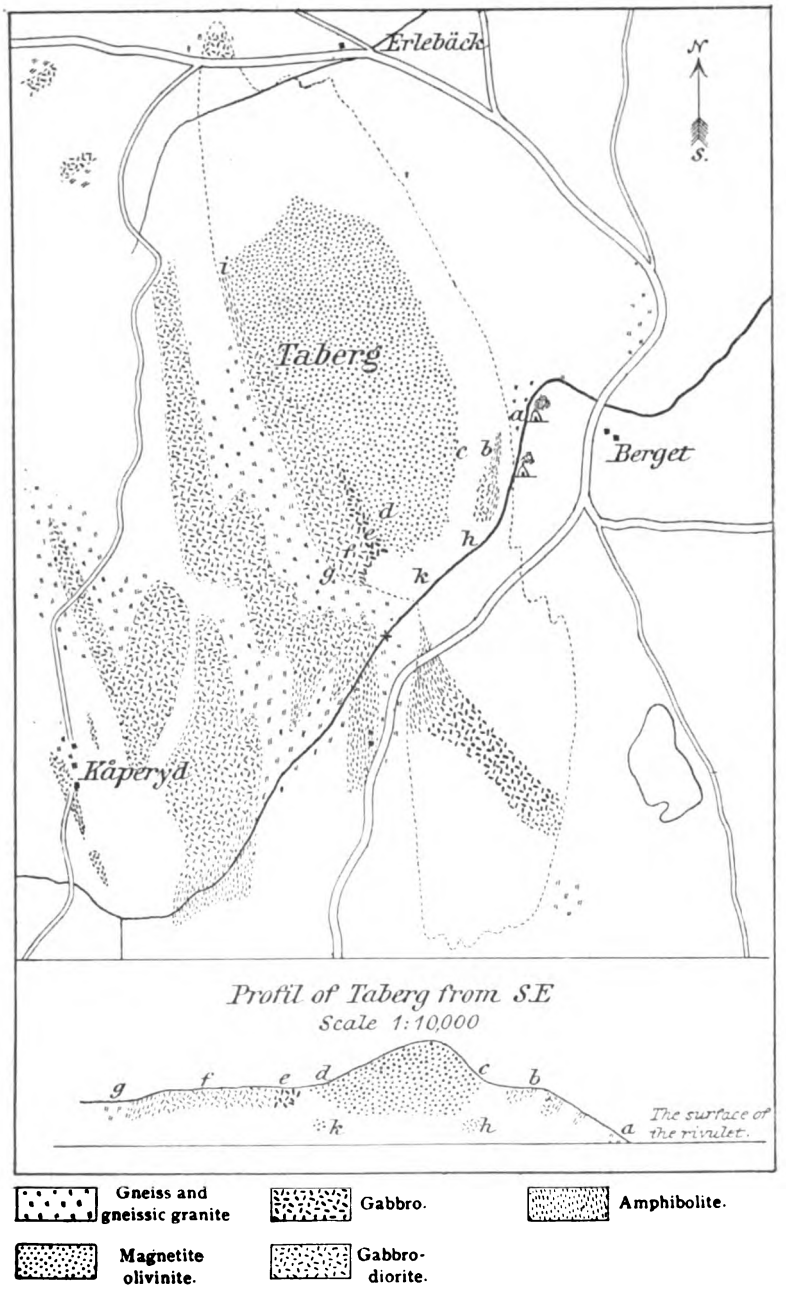

FIG. 14.—TABERG (Törnebohm).

olivine and has received the petrographical name magnetite-olivinite. Where it approaches the normal rock, it first takes up plagioclase, then pyroxene, so that there is a transition from the ore to the normal rock, which also contains magnetite and olivine. The ore-stock thus forming the kernel of the mountain is next surrounded by a shell or mantle of normal gabbro, which, in its turn, towards the inclosing gneiss, passes into the schistose, dynamo-metamorphic border-facies, the gabbro-amphibolite.

The ore is poor throughout, carrying generally from 20 to 30 per cent. of iron. Vein-like segregations containing up to 60 per cent. occur as rare exceptions. Titanic acid varies between 4 and 6 per cent.; the percentage of phosphorus does not exceed 0.1; to which may be added a constant percentage of vanadine.

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[ABRIDGED SUMMARY.—Minor deposits in central and southern Sweden, and several in Norway, belong to this class. And in the small islands along the coast of Angumanland occur similar segregations in a diabase younger than the Dala sandstone, forming, between stratified quartzites, bed-like intrusions which have been exposed by erosion. The darker bands of this rock have acquired, in some places, through a concentration of titano-magnetite, the character of iron-ore. The proportion of titanic acid may amount to 25 per cent. In the island of Alnö concentrations of titano-magnetite in a boss of nepheline-syenite have been worked in a small way as iron-mines. At Ekersund and Soggendal, in Norway, deposits of iron-ore occur in a colossal laccolite of highly differentiated basic rocks, supposed to be of post-Silurian age. They have been worked at different times, but without commercial profit, since they contain, as an average, only 40 per cent. of iron, and from 40 to 42 per cent. of titanic acid. Deposits of this class are numerous along the coast of Norway, in laccolites laid bare by the fjords. One of the largest in Scandinavia is that of Routivare in Norrbotten, which was formed by segregations in an intrusive rock, occurring as a laccolite in the metamorphic Silurian formations.]

Summary.

Though the rocks which inclose the deposits of this class differ in composition (as real gabbros, norites, diabases, or nepheline-syenites), as well as in age (some of them belonging to the oldest Archæan formation, and the youngest dating from post-Silurian time), yet a marked degree of basicity seems to be a necessary condition for the formation of such concentrations. Vogt puts the highest acidity at 57 per cent. of SiO_2. The majority of the deposits occur in rocks with a silica-percentage of from 48 to 54 per cent. The different facies of gabbro-rocks inclose deposits of different character. The pure

ilmenite-segregations (Ekersund, Soggendal, Lofoten, etc.), seem to be confined to the labradoritic rock. In the same rock-series we also find the ilmenite-norite. In the olivine-gabbro, rich in magnesia, which incloses the deposit of Taberg, the segregation has assumed the mineralogical character of magnetite-olivinite, and in the rocks which are richer in alumina, magnetite-spinellite has been segregated, as at Routivare, Andopen, on Stjernö in Finnmarken, and elsewhere.

A remarkable feature of the ore-concentrations in question is their occurrence, almost without exception, in the central parts of the eruptive masses. This gives them a character different from that of those concentrations of basic constituents in an eruptive rock which are often met with along the margins of rock-veins, and in which the enrichment has not proceeded so far as to form an iron-ore.

As to the degree of concentration of the iron, the ore-types differ also from one another. The concentrates richest in iron are the magnetite-spinellites, with an iron-percentage exceeding 50 per cent. (Routivare, 50 to 54; Solnör, 54; Hellevig, 51; Andopen, nearly 60). Next to these come the segregations of the nepheline-syenites, of which in Alnö some contain from 46 to 53 per cent.; and after these the ilmenite-segregations in the labradoritic rock and the norite, with about 40 per cent. of iron, and nearly as high a percentage of titanic acid. Poorer still are the ores of the olivine-gabbros of the Taberg type, which contain little more than 30 per cent. of iron. Comparable to them are the ores of the olivine-diabase (the Ulfö type), with about 34 per cent. At the bottom of the scale stands the ilmenite-norite, the Storgång type, with about 21 per cent. of iron.

Besides the iron, it is chiefly the titanic acid, the magnesia, and the alumina that have been concentrated. The percentage of titanic acid is highest in the ilmenite-segregations of the labradorite and norite, where it amounts to from 39 to 43 per cent.; next come the ilmenite-norites, which contain 18 per cent.; the magnetite-spinellites (type Routivare) vary between 10 and 18 per cent.; the segregations of the nepheline-syenite show about 10 per cent. (the Trygg mine, in Alnö, from 9.10 to 12.14); in the Taberg type, the magnetite-olivinite, the percentage of titanium, like that of iron, is the lowest—viz., 6.30

in the Taberg ore and 8.50 in the ore of Långhult. The Ulfö type, with about 10 per cent. of TiO_2, shows the greatest agreement with the Taberg type.

The concentration of magnesia has taken place not so much in the ore as in the concentration-facies between the normal rock and the segregations richest in iron. It manifests itself in the formation of Mg-Fe silicates of the olivine and pyroxene groups. The rock-facies, which have received the names magnetite-olivinite, ilmenite-norite, and ilmenite-enstatite, have originated in this way. A certain percentage of Mg is found even in the purest segregations of ilmenite in the labradoritic rock, owing to a mixture with $MgTiO_2$. The alumina left in the final concentrates combines particularly with the magnesia, thus forming spinel, the formation of which is favored by the relation-deficiency of silica in the magma. This mineral occurs in the following ore-types: the magnetite-olivinite (Ransberg); the ilmenite-norite (Ekersund); and the magnetite-spinellite (Routivare, Hellevig, Lofoten, and Stjernö). Vogt has called attention to the fact that the Mg-percentage increases in the first stage of concentration and then diminishes. While the original magma contains more Al_2O_3 than MgO, the case is quite the reverse in the earlier stages of concentration. In the final product, however, the amount of alumina again exceeds that of magnesia.

Besides the aforesaid substances, chrome and vanadium, which occur in small quantities, have undergone a concentration. The phosphorus, on the other hand, is not in general concentrated to any noteworthy degree. To this, however, there are exceptions, such as the segregations of ilmenite-norite traversing the labradoritic rock in the Soggendal-Ekersund field, which contain a fairly high percentage of phosphorus, while the surrounding rock carries little, and the above-mentioned concentrations, rich in apatite, in the hypersthene-gabbro at Krekling, Norway, and also in the nepheline-syenite of Alnö.

That silica, lime, and alkalies occur in smaller quantities in the concentrates than in the rest of the rock-mass is manifested mineralogically by the total absence of feldspar from these concentrations.

Vogt has pointed out[22] that in several places in Lofoten and Vesteraalen, in the labradoritic rock containing olivine and hypersthene, there are besides segregations of magnetite-dialagite, also *schlieren*-like segregations of pure olivine rock as well as of hypersthenite. This shows that in the same magma differentiation processes following different lines have taken place nearly contemporaneously. As extreme basic segregations the limestones occurring in the nepheline-syenite may also be explained.

Many different attempts to suggest the cause of these differentiations have been made, but no satisfactory explanation has as yet been proposed.[23] It seems as if, with respect to this kind of segregations, the view according to which the magma is regarded as a mixture of different liquids, partly insoluble in one another, were decidedly preferable to the theory which considers the laws of dilute solutions applicable to the magma. The principle of limited solubility must be considered as the physico-chemical principle governing the differentiation-phenomena of silicate-magmas in general.

Neither "Soret's principle," nor any other form of the theory of diffusion, nor "connection currents," nor the magnetic attraction of the "liquid molecules," nor the different weight of the segregated solid constituents can afford an explanation of differentiation-phenomena of this kind. The geological conditions also seem to harmonize better with the view which connects the differentiation with the segregation and solidification of liquids insoluble in the remaining magma. These are separated out in consequence of the cooling of the magma, by which the conditions of solubility are changed, or of the escape of water or other mineralizers; the segregation takes place at first in the form of drops throughout the magma, which drops, on account of the surface-tension, have a decided tendency to coalesce and flow together into *schlieren* and larger concentrations. Which of the liquids is attracted to the side-walls and solidifies there, and which of them solidifies in the center, will in each case depend on the relative force of the adhesion to the side-walls.

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[22] *Zeitschrift für praktische Geologie*, vol. xiv., pp. 217 to 233 (1906).

[23] Vogt, *Zeitschrift für praktische Geologie*, vol. ix., pp. 327 to 340 (1901).

Analogous Deposits.

Titaniferous iron-ore segregations in basic eruptive masses constitute a well-defined class, which has representatives in all parts of the world. Several of the different types found in Scandinavia occur in other countries also.

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The magnetite-olivinite or Taberg type is analogous to the deposit at Iron-mine Hill in Cumberland, R. I., described by Wadsworth, though the latter is of smaller dimension. The "gabbro titanic-iron-ores" of the Mesabi range in Minnesota, described by N. H. and H. V. Winchell, also seem to come very near to the type, though the concentration of the iron and the titanium has in these ores proceeded further. Among the segregations occurring in large masses in the various gabbro and labradoritic rocks of the eastern Adirondacks, the Taberg as well as the Ekersund type is represented.

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[A discussion of the geological horizon of this group, and descriptions of Dunderland, Naeverhaugen, Salangen, etc., follow.]

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Summary.

The deposits of this group belong to a ferriferous formation of vast horizontal extent, occupying nearly the same geological horizon in the series as the mica-schist-marble member of this sedimentary series. The ferriferous formation occurs regularly associated with limestones, in most cases, however, in the schists underlying the limestone. The connection with the limestone is so strongly marked that in certain districts nearly every limestone bed is accompanied by iron-ore; some observers have even been inclined to assume a connection between the thickness of the limestone beds and the size of the iron-ore deposits.

Mineralogically, the ores are characterized as mixtures of magnetite and specular hematites; and further, by the occurrence of iron-magnesia-lime silicates of the amphibole, augite, epidote, and garnet groups. Quartz is always present in large quantity. Chemically, these ores are characterized by a high percentage of silicic acid, low percentages of CaO, MgO, and Al_2O_3, a medium percentage of phosphorus, and small amounts of sulphur and titanic acid. Whether these ores are primary sedimentary deposits or secondary concentrations of leaner iron-bearing formations is still an open question of the greatest practical importance.

These ores have, *e.g.*, in Dunderland, an extent of several kilometers in length and, at the same time, a considerable thickness. If, taking the syngenetic point of view, we regarded these ores as ordinary stratified formations, altered only by regional metamorphism, we would have to assume an extent of several kilometers in the direction of the dip. Such a conclusion might be highly misleading with regard to the ore-supply. As to the depth which the ores of this kind reach, there is as yet no practical experience, as neither exploratory work nor even any borings below the present or former ground-water level have been performed.

A comparison with the Archæan ores of Group I. shows, it is true, some points of agreement. On the whole, the primary characters of chemical sediments are much more evident in this class of ores than in the Archæan ores. Above all, the trans-

formations in the anamorphic zone are less marked; this is shown by the gangues being less developed and the alteration into magnetite less advanced. No analogies to the large magnetite-stocks among the Archæan ores are found here. Although the nearness to the magnesian limestone has offered plenty of material for the formation of lime-magnesian silicates of the pyroxene, amphibole, and garnet groups, these silicates never are formed in such abundance as to compare with the *skarn* gangue of the Archæan ores. The interchange of constituents between the schist, the iron-ore, and the limestone, lying close to one another, has been rather limited. Probably also the submersion in the anamorphic zone did not go so deep as to reach a temperature high enough for the formation of anhydrous silicates on a large scale. The depth and the temperature under which the crystallization of these ores occurred seem to have been better adapted to produce the slightly hydrated silicates of the epidote group.

The transformations in the catamorphic zone also are less marked; one finds no concentrations of so great richness, no "*sköl*"-formations, and no accumulations of ores in pitching troughs or on impervious basements. The ores are of more equal leanness, and in general the concentration does not exceed 40 per cent. of iron.

On the whole, one may consider these deposits as the roots or the deepest, comparatively unconcentrated parts of regional metamorphosed chemical depositions, laid open by the deeply penetrating fjords and valleys of the Norwegian coast; the upper, probably more concentrated and richer parts of the same deposits, having been destroyed by erosion.

Analogous Deposits.

The ores of this class are in many respects comparable to those of the lower Silurian formation in the eastern United States, especially to those occurring in a belt from Vermont to Alabama. These ores occur only where the lower Silurian limestone and the Hudson shales meet, as the Norwegian ores always occur at or near limestones, sometimes dolomitized. This is, indeed, one of their most important geological characters. The Norwegian rock-strata are, of course, more metamorphosed, the rocks consisting of crystalline schists and mar-

ble or magnesia-limestone, and the ores being specular hematite or magnetite, instead of red and brown hematite. The Clinton ores likewise show, with regard to geological conditions, great agreement with the Norwegian Palæozoic ores.

GROUP V.—CONTACT-DEPOSITS IN THE CHRISTIANIA REGION.

These ores were considered by Keilhau, Daubrée, and Kjerulf as genetically connected with the intrusion of granite in the same region; and this opinion was afterwards confirmed by Vogt, who executed a minute survey of the deposits.[27]

Classification of the Rocks.

According to Brögger, the igneous rocks of the Christiania region may be divided into seven groups of different age; the oldest three are more basic, and consist of (1) gabbro-diabases; (2) basic augite-, mica- and nepheline-syenites (laurvikite and laurdalite); and (3) quartz-bearing augite-syenite (akerite). Of later age is the following syenitic and granitic series, comprising (4) red quartz-syenites (nordmarkite); (5) soda-granites (grorudite); and (6) granitite. As the youngest members occur dike-forming diabase and diabase-porphyrite. The eruptives are probably of Devonian, surely of post-Silurian, age. They occupy an area about 250 km. long, and in some places more than 100 km. wide.

The intrusives are bordered partly by Archæan rocks, partly by the Silurian strata, and by porphyry-outflows. The contact-deposits are found in all these different pre-granitic rocks.

Most of the deposits are connected with the red quartz-syenite (nordmarkite), some of them with the soda-granite (grorudite) and the granitite.

The Ores.

The iron-ores are, as a rule, mixed with true contact-minerals, such as different species of the garnet and vesuvian groups, scapolite, wollastonite and others. This is especially the case with the deposits occurring in the limestone and marly slates. In the clay-slate, chiastolite is found as contact-mineral. The percentage of iron is through the gangue reduced to from

[27] *Zeitschrift für praktische Geologie*, vol. ii., pp. 177, 464 (1894), vol. iii., p. 154 (1895).

30 to 35, and only exceptionally exceeds 40. The ores are generally strongly pyritic, but low in phosphorus and titanium. Frequently they occur in the immediate vicinity of the intrusive rock, but they may also be found up to 1 km. from the contact. In a few cases the distance from the visible contact is more than 1 km., but the ores never are found outside of the metamorphic zone of the contact. The majority of the deposits occur in the Silurian strata, partly at the borders of the Silurian rocks, partly in big metamorphosed Silurian rock-fragments, completely surrounded by the igneous rock. The different Silurian horizons are equally impregnated with ores; and the clay-slates as frequently contain ore-deposits as do the limestones and marly slates. Also, the Archæan gneisses, and sometimes the porphyries, are ore-bearing.

The ore-deposits show generally a stratiform extension, and may be followed with varying thickness along the same bed for several hundred meters.

These deposits, though numerous, are quantitatively too insignificant to play any commercial rôle. In earlier times several hundred small ore-bodies were worked. The ore is mainly magnetite, but also specular hematite. Also, sulphides of iron and copper occur in so great amount that the ore may obtain the character of a copper-ore. Exceptionally, also, galena and blende have been found in such quantities as to be mined as ores. But all the deposits are small. From the seventeenth up to the latter part of the nineteenth century, they furnished a group of small blast-furnaces with iron-ores; and an insignificant copper- and lead-production was in early times based on these ores.

Analogous Deposits.

The ore-deposits of the Christiania territory are genetically most similar to the Pitkaranda deposit in Finland, and the known deposits of Schmiedeberg in Silesia and Berggiesshübel in Saxony.

There are a great number of deposits of this kind in the western United States, chiefly in Colorado and California, where they occur associated with the younger eruptives of the Rocky mountains and the Sierra Nevada.

Group VI.—Lake- and Bog-Ores.

These ores formed the raw-material for the oldest iron-industry in Scandinavia, long before the blast-furnace process was known. For this reason, Carl Linnæus called them *Tophus Tubalcaini*, after Tubal Cain, the first blacksmith (Gen. iv, 22). The lake-ores occur in most provinces of Sweden and in the southern part of Norway. But their abundant occurrence is confined to regions where the ground consists of moraine and glacial gravel and sand, especially the high plateau of Småland, the northern parts of Vermland, Vestmanland and Dalarne, and the greater portion of Norrland. They occur only sparingly in the regions covered by glacial and post-glacial marine-deposits, such as the lower coast-belt of southern Sweden, and the plains surrounding the great lakes of Vänern, Vettern, Hjelmaren and Mälaren. In short, the lake- and bog-ores are most frequent above the marine level of the glacial period. A certain connection with the distribution of the peat-mosses is indicated. On the other hand, the bog-ores are by no means more frequent in the districts rich in other iron-ore deposits. In some places, a connection with the greater pyrite-deposits may be suggested.

The bog-ores are recent formations, produced before our eyes. In lakes, where the ore has once been exploited, it grows and may be utilized again. In some lakes of Småland mining-operations have been resumed at places exhausted 25 years before.

In the ore-bearing lakes, the iron is precipitated from dilute solutions chiefly along certain zones, parallel to the shores, at a depth of from 2 to 4 m., and the ores are thus distributed in belts on the bottom of the lake, to a thickness of at most 0.5 m. Lakes connected by a water-course frequently all contain bog-ores. In the upper lakes the ore is more fine-grained ("gun-powder-ore," "pearl-ore"), while in the lower lakes the ore has grown to coarser concretions ("money-ore," "cake-ore").

The purer lake-ores generally contain from 50 to 60 per cent. of Fe_2O_3 and from 10 to 15 per cent. of water. Silicic acid is frequently mechanically intermixed, reducing the iron-percentage. Sometimes the ores contain a considerable amount of manganese (up to 20 per cent.). The percentage of phosphorus as well as of sulphur is generally high.

Bog-ores are often formed in lakes as lake-ores, and later, by a natural draining, brought above the water-level. But frequently bog-ores occur in a manner indicating their formation in the ground close to the surface; in such cases they are often formed in connection with peat-mosses.

The utilization of the lake-ores has in later years much decreased, and is to-day without importance. From 1860 to 1875 the annual production in Sweden was about 10,000 tons. From 1900 to 1905, it was only about 1,000 tons, varying from 300 up to 1,500 tons, according to the severity of the winters. The whole product comes from Småland and is used for the fabrication of cast-iron.

No. 27.

The Formation and Enrichment of Ore-Bearing Veins.

BY GEORGE J. BANCROFT, DENVER, COLO.

(New York Meeting, April, 1907. *Trans.*, xxxviii., 245).

Introduction.

It is unnecessary to repeat here the contents of many valuable contributions to this subject which have appeared in the *Transactions* and in the publications of the U. S. Geological Survey. As a basis for the further suggestions of this paper, the following are the most important:

1. The investigation of J. R. Don,[1] showing the gold of certain Australasian veins to have been deposited by ascending solutions, and not by lateral secretion.

2. The theory of Prof. Posepny,[2] distinguishing the vadose from the deep circulation, and ascribing the origin of certain classes of ore-deposits to ascending solutions of the latter class.

3. The theory of Prof. Van Hise,[3] as to the underground circulation and the primary enrichment of veins thereby.

4. The paper of Prof. J. F. Kemp,[4] showing that ore-deposits are largely the products of "expiring vulcanism." Many of Prof. Kemp's ideas have been widely adopted by mining men.

5. The theory of secondary enrichment, so lucidly expounded by Mr. S. F. Emmons.[5] This theory, dealing with the rearrangement of ore-bodies after primary mineralization, has been generally adopted, and seems to me to have been as completely proved as the nature of the case permits.

There are two facts which I think should be constantly borne in mind in formulating a theory of the genesis of ore-

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[1] The Genesis of Certain Auriferous Lodes, p. 162, this volume.

[2] *Genesis of Ore-Deposits*, pp. 1 to 187, and *Trans.*, xxiii., 197 to 369 (1893).

[3] Some Principles Controlling the Deposition of Ores, *Genesis of Ore-Deposits*, pp. 282 to 432; also, *Trans.*, xxx., 27 to 177 (1900).

[4] The Rôle of the Igneous Rocks in the Formation of Veins, *Genesis of Ore-Deposits*, pp. 681 to 709; also, *Trans.*, xxxi., 169 to 198 (1901).

[5] *Genesis of Ore-Deposits*, p. 462, and *Trans.*, xxx., 206 (1900).

bodies. The first is that commercially valuable mines are relatively few. Countless veins present all the characteristics of good mines, except the values. I suppose that there are a hundred barren veins for every enriched one, and even the latter are rarely enriched to the extent of more than 20 per cent. of their volume. The stope-map of any old mine, showing the proportion of stopes to barren ground, will very seldom indicate that more than 20 per cent. of the vein has been removed.

The second fact is, that nearly all ore-bodies are found in close association with eruptive rocks. So generally is this fact recognized that an old mining man does not like to spend money on a prospect in a new district where there is no "porphyry" ("porphyry," in the broad miners' sense, meaning any kind of eruptive rock).

In view of these two facts, it seems to me that any theory which does not recognize that only exceptional conditions could produce such exceptional results of enrichment, which does not recognize and explain the relationship between "porphyry" and ore, falls short of the mark.

My own observations as a mining engineer have led me to the following tentative views: (I.) that the majority of mineralized veins are the product of expiring vulcanism; (II.) that most of these veins were primarily mineralized by comparatively rich solutions in comparatively short periods of time; (III.) that the solutions derived their metal-values from a comparatively rich source; (IV.) that there is a barysphere containing large amounts of the useful metals; (V.) that eruptions spring from various depths and bring various kinds of magma towards the surface; and (VI.) that only those eruptions which disturb the barysphere, and bring a magma rich in metals sufficiently near the surface to be leached by vein-making solutions, are productive of valuable ore-deposits, other eruptions producing barren veins.

Ore-bodies due to magmatic segregation are not included in this general survey.

These propositions will be successively considered in the present paper.

I. The Majority of Mineralized Veins Are the Products of Expiring Vulcanism.

This proposition has been so fully demonstrated by Prof. Kemp in his very valuable article entitled The Rôle of the Igneous Rocks in the Formation of Veins,[6] that I feel it would be superfluous to add much to it.

There is, however, one small matter in which I differ with Prof. Kemp—namely, I do not think there is good reason to believe that the surface-water does not sink down into the rocks to very considerable depths. Prof. Kemp notes that many mines are dry to the point of being "dusty," at depths below 1,000 ft. This is true; but in a drift which is being rapidly driven the freshly-broken breast will always be found to be damp. The reason the lower levels of so many mines are dry and dusty is that the evaporation, slow as it is, is nevertheless faster than the very torpid movement of the ground-water. This torpidity of the ground-water in depth is caused by the "tightness" of the rocks. It is a familiar experience in mining that the ground gets tighter the deeper one goes. Of course, in individual districts there may be other obstacles, such as sills of impervious rocks or clay, preventing the ground-water from sinking into the lithosphere; but, in almost every case known to me, the tightness of the rocks in the lower levels will account for any observed diminution of water-flow. Where recent fissuring has occurred, there is generally no diminution of water-flow with depth. Indeed there may be, as at Cripple Creek, an increase.

It is often overlooked, in discussing the saturation of the ground, that in many mining districts the yearly evaporation is greater than the yearly rain-fall less the run-off. This question has been very extensively studied by the U. S. Hydrographic Survey. One of its publications, entitled The Relation of Rain-fall to Run-off, sets forth data on this subject gathered in many places. No general conclusions are drawn; but I figure that in Colorado the run-off is about one-third the rain-fall. The rain-fall varies from 12 to 24 in., or, after deducting the run-off, we have from 8 to 16 in. per year. The capacity for evaporation is more than 3 ft. per year; so that, except in those channels

[6] *Genesis of Ore-Deposits*, pp. 681 to 709, and *Trans.*, xxxi., 189 to 223 (1901).

where water quickly gathers after a rain, the country must be in a state of continual thirst, and only such water will remain under ground as is held there by capillary attraction. As depth is gained and the water-gathering channels become less frequent, we find the rocks to be moist but not always wet. Similar conditions prevail in many mining regions.

Prof. Van Hise has drawn attention to what he calls the zone of flowage, which begins at depths of from 5,000 to 12,000 m. To my mind the zone of flowage is more a matter of time, and less a matter of depth, than he considers it. I think a channel may exist at much greater depth than his limit for a short time, but when a long time is involved, I think the zone of flowage may come very close to the surface.

It seems to me entirely logical to suppose that a channel may remain open as long as it takes a laccolite to cool and yet gradually close till it is tight, except where quartz or other vein-matter has formed in it. A channel that would stay open when the surrounding rocks were quiet would have a strong tendency to close gradually if those rocks were subjected to forces which cause flexure or other movement in the earth's crust. If this supposition be well founded, it will account for those cases where the quartz is in lenticular masses and mere tight cracks in the rocks represent the veins beyond the limit of any lenticles. Such cases simply indicate that the channels have closed since the vein was formed. It is noticeable that such veins are often found in schist, or other rocks that show the effect of movement and pressure. The matter of open channels is further discussed under my third proposition.

In districts which have been fissured quite recently, like Cripple Creek, we find open fissures and much water as far down (about 1,500 ft.) as the deepest shafts have gone. But even in this camp the deep shafts in the granite are nearly dry at the bottom. Whether this is because the granite was fissured less than the eruptive rocks in the first place, or because the granite is more mobile under pressure and has closed in on its fissures, I am not prepared to say. At all events, the shafts in the granite are dry at horizons where shafts in the eruptive rocks are troubled with a great deal of water; and this water has been conclusively proved to be simply rain-water stored in the vast underground reservoir formed by the countless open

fissures in the eruptive rocks. There are no volcanic springs active in Cripple Creek to-day. Hence, I think Prof. Kemp gives a wrong impression, and one which he probably did not intend, when he says that many mines are dry to the point of being dusty in depth, which were wet near the surface. I believe that the earth is very generally impregnated with moisture; but I quite agree with Prof. Kemp that this "sea of underground water" is utterly inadequate to account for ore-bodies. In most formations, there is practically no movement in this water below the 500-ft. level. In many cases it will not run into a mine fast enough to equal the slow evaporation; and it is beyond conception that such a torpid agent could accomplish anything in the line of vein-making before a fissure would close up, even at moderate depths.

All mining men have met with "swelling ground," and most of them have known of swelling ground that could not be accounted for by the action of the air admitted by the mine-workings. This kind of swelling is, of course, very much slower than that due to the "slacking" of lime or other rocks influenced by the air; but it shows the general tendency of rocks to close up any opening beneath the surface. Yet this tendency is always a function of time, and time is one of the most puzzling factors in any geological discussion.

It is impossible to state in years how long a geological operation lasted. The most that can be done is to compare the duration of one geological operation with that of another. To my mind, most ore-deposits show that the time consumed in their formation was very short, compared, for instance, with the time necessary to carve out the canyon of the Colorado; hence, I think that a fissure that would in time close up tight, might nevertheless stay open during the (geologically) brief interval required to cool a mass of eruptive rocks.

II. Most of These Veins Were Primarily Mineralized by Comparatively Rich Solutions in Comparatively Short Periods.

That considerable mineralization has been effected where the solutions passed through very small channels, leaving those channels very little altered, is evidenced in many places. The so-called "flats" of the Black Hills are cases in point. In the

Penobscot mine, for instance, several flat deposits of gold-ore in the sedimentary rocks have been extensively worked. The ore occurs in shoots averaging perhaps 45 ft. wide and 4.5 ft. thick. Each ore-shoot has a vertical fissure coming up through the so-called "quartzite" beneath it; and over these fissures the richest ore is found. These fissures are so small as to be easily overlooked. Those that I saw varied from 0.125 to 0.675 in. in thickness. In some places they were open, while in other places, where the width was about the same, they were filled with quartz, a circumstance which indicates that these fissures have not closed up to any great extent.

That such extensive ore-bodies should be mineralized through such small fissures suggests strongly that the solutions were comparatively rich and that they flowed for a comparatively short time. A long-continued flow, I think, would have either enlarged the little fissures or filled them completely full of quartz.

The Cortez mine, Nevada, and the Lisbon Valley copper-fields of Utah are also cases in point. At these places mineralized solutions came up through hard strata of sedimentary rocks and spread out in soft porous strata, mineralizing considerable areas. In both localities the vertical fissures are small, and show little alteration of the wall-rocks. From specimens I have seen which were brought from Cobalt, Ontario, Can., I would say this is another case in point. The specimens show solid sheets of silver between comparatively unaltered walls.

That the lavas issuing from volcanoes contain large quantities of steam is well known. During the early stages of the eruption of Vesuvius, in 1898, I observed a small lava stream on two occasions, about 6 days apart. The stream was about half a mile long, and was moving very slowly. I presume it had taken three weeks to gain this length, yet it was spitting steam continually from every pore throughout its entire length. I was much impressed with two things: the great amount of steam escaping from a stream 15 ft. wide and 4 ft. deep; and the fact that the lower end continued to advance when it had only a very dull red heat. I wondered whether the escaping steam did not account for its mobility in some way. If all magmas have stored in them as great quantities of water as the Vesuvius lavas and if they tend to discharge it when brought into condi-

tions of lessened pressure we have here a source of water of no small moment. It is hardly conceivable, however, that this source can alone supply all the water used in vein-making in all cases. For instance, if a magma contained as much as 25 per cent. of water, then a spring running 10 miners' inches would in 200 years exhaust a body of the magma 40 ft. thick and 3,600 acres in extent. I think we must agree, therefore, that in some cases the volcanic waters are serviceable principally in starting and maintaining open waterways and establishing a current. In such cases they are probably joined by other waters, and the combined flow accounts for the volume of water which we find issuing from some mineral springs. Thus we find ore-deposits, such as the immense quartz-veins of the San Juan, in Colorado, or the big quartz-lenses of the Homestake, in S. Dakota, and of the Mother Lode, in California, that seem to have been formed by a generous supply of water; and we find other ore-bodies which indicate that very little water ever circulated through the veins, as, for instance, the ore-shoots of Goldfield, Nev., which occupy single cracks or net-works of cracks, made since the big quartz-reefs were formed, and in which angular corners of the walls frequently stick out into the solid masses of sulphide ore. As the ore-bodies are found in the easily altered country-rocks as well as in the quartz-ledges, such angular corners are the more remarkable. If the mineralized solutions had run a long time, these corners would have been rounded off.

At Cripple Creek, likewise, we find areas where the joints and seams of the country-rock are coated with sylvanite, and where there is no other evidence of vein-making agencies. In the veins themselves silicification is very slight. Kalgoorlie, West Australia, where a great deal of enrichment has taken place with very little silicification or other alteration of the country-rock, is another illustration. Such camps are irreconcilable, in my mind, with the theory that veins were formed by very lean solutions acting through long periods of time. Even the big low-grade quartz-veins seem to indicate an agent much more active than is generally recognized. To my mind, the evidence suggests that some ore-bodies were formed by the magmatic waters or vapors alone, while others were formed or rearranged by considerable volumes of water. There is some reason to believe that the quartz of an ore-body is not always a

full-blooded brother to the mineral contents of that body; but I will not discuss that matter at this time.

In most genetic processes nature is extremely wasteful. In the formation of a sand-bar in the Mississippi river, hundreds of tons of material pass down the river every day; but it is only an occasional grain that lodges on the sand-bar. Or in the growth of mounds around mineral springs, the water that flows over them is all charged with mineral matter but it is only an occasional atom that lodges on the mound. In view of this consideration, it seems to me that the theory that ore-deposits were formed by leaching the extremely lean, eruptive, or other rocks known to us on the surface, involves one of two rather untenable suppositions. Either we must conclude that nature has operated with a degree of accuracy which is almost unattainable in the laboratory; that she has leached absolutely clean the metal-contents of a rock which had the merest trace to start with, and that she has precipitated every bit of the metal so gathered in an ore-body, leaving the solution absolutely barren; or else, in case it is admitted that nature probably operated with her usual prodigality, we must assume that a tremendously large mass has been subjected to leaching action to form a relatively small ore-body. In accounting for a large ore-body, such as those of our leading copper-camps, it is difficult to understand how the leachings from such a great area as this hypothesis necessitates could have been gathered together into one underground channel. We are forced to assume that veins must branch out downwardly like the limbs and twigs of a giant tree inverted. Such conditions are contrary to ordinary observation. Veins not infrequently unite as depth is gained, but very seldom branch out with depth. This again leads to the conclusion that the solutions that formed ore-bodies were not the extremely dilute solutions which would result from leaching lean rocks.

Another reason for believing that ore-bodies were formed from comparatively rich solutions is the well-known difficulty of precipitating the last trace of any metal in solution. Whoever has had to do with a leaching process, such as cyanidation or chlorination, knows how difficult it is to get into solution the last trace of gold in the ore, and to precipitate the last trace of value from the solution. In fact, this is practically impossible;

tailings carrying from 30 to 60 cents per ton are considered in most cases to indicate good work; and foul solution that contains no more than 20 or 30 cents of value per ton is considered poor enough to throw away. Yet the surface-rocks, considered by some to be the source of the metals, are much leaner than the poorest tailings; therefore, solutions picking up metals from them must be poorer than the solutions we are forced to discard as worthless—in fact, not less dilute than the sea-water, which Don found to contain 0.071 grain of gold per ton of 2,240 lb. Don was unable to precipitate directly from this sea-water any gold at all, although he used the best precipitants under the most favorable conditions. He made his determinations by slowly evaporating several tons of sea-water and assaying the residue.

As to the time occupied in forming veins, it seems to me that most of the work has been done during the period that Prof. Kemp so fittingly calls that of "expiring vulcanism." This is a relatively short period—so short, in fact, that changes in its conditions may be noticed within a human life-time. Hot springs are very generally associated with expiring vulcanism; and nearly all the hot springs that I know of are noticeably drying up. At Steamboat springs, Nevada, at least two borings have had to be made to bring the flow up to its original capacity. Old settlers at Glenwood springs, Colorado, testify that hot water used to issue from a number of minor vents which are now dry, and that the main streams are slowly decreasing in flow. At Aguacaliente, in Sonora, the water is used for irrigation, and the abandoned fields farthest down the gulch bear mute testimony to the gradually decreasing flow. This spring is a fine example of the fact that hot mineral springs have some source other than rain-water. The only range in this dry country that receives any rain-fall to speak of is the Sierra Madre, 100 miles east and across the Yaqui valley. The largest cold springs within a radius of 20 miles are only large enough to supply water for domestic use.

In discussing mineral springs, it must be borne in mind that some of them are no doubt of secondary origin. Thus, Trimble springs, Colorado, gives every evidence of having received its heat and mineral contents from the oxidization of a large body of iron pyrites.

TABLE I.—*Analyses of Eruptive Rocks from the Telluride, La Plata and Port Orford Quadrangles.*

No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
SiO_2	64.72	65.70	52.05	47.32	59.79	57.42	55.53	60.44	43.98	47.75	39.42	38.55	54.19	50.14	60.88	56.48	57.43	50.56	52.12	53.06	71.45	70.38	75.32
TiO_2	0.43	0.72	.....	1.50	0.67	0.86	0.95	0.60	1.18	1.22	.....	tr.	0.12	1.42	0.41	0.31	0.66	1.67	1.38	0.42	0.16	0.27	0.16
Al_2O_3	14.18	15.81	17.96	16.92	17.25	18.48	16.78	16.67	13.30	15.19	1.39	1.32	10.66	15.26	17.71	13.81	17.69	14.49	15.21	12.83	14.53	15.74	13.17
Fe_2O_3	1.58	2.54	4.09	6.21	3.60	3.74	4.06	2.31	3.67	5.05	3.42	5.55	0.52	1.19	2.92	1.73	1.59	1.78	1.83	1.20	0.49	1.43	0.27
FeO	0.40	1.62	6.33	5.94	1.59	2.10	3.35	3.09	6.92	4.95	4.29	2.17	2.26	8.75	2.17	3.95	3.48	10.20	8.75	5.10	0.94	0.83	0.98
CaO	2.62	2.56	8.64	8.51	3.77	6.84	6.96	4.22	10.66	9.98	1.10	0.85	10.76	9.34	4.32	6.69	5.72	10.13	3.75	13.71	2.01	3.38	1.48
BaO	0.28	0.12	.....	0.07	0.14	0.15	0.13	0.12	0.06	0.08	.....	.....	0.04	0.03	0.06	tr.	.....	tr.	.....	.....	0.03	0.09	0.23
SrO	0.21	0.03	.....	0.06	0.11	0.08	0.11	0.11	0.05	0.05	.....	.....	0.05	.....	.....	0.02	0.02	.....	.....	.....	.....	.....	0.02
MgO	0.50	1.62	5.03	5.69	1.24	1.71	3.00	2.18	7.03	6.87	39.68	39.06	11.90	7.21	2.21	8.67	2.73	5.90	6.01	7.50	0.30	0.53	0.42
K_2O	1.82	4.62	1.61	2.02	5.05	3.71	3.57	2.71	1.64	2.60	none.	0.05	1.03	0.95	2.68	0.46	0.58	0.38	0.48	0.05	2.55	1.87	2.14
Na_2O	3.88	3.62	2.99	2.70	5.04	4.52	4.31	5.18	2.15	2.39	.....	0.10	1.35	2.76	4.17	5.03	7.19	2.91	4.83	3.56	7.15	4.33	4.77
P_2O_5	0.08	0.33	0.31	0.96	0.35	0.36	4.47	0.29	0.32	0.25	.....	tr.	tr.	0.24	0.16	0.02	0.18	tr.	0.14	tr.	0.09	0.06	0.04
H_2O	9.50	0.59	0.97	1.28	0.58	0.36	0.64	1.43	1.94	2.52	9.89	11.28	5.93	2.45	2.01	2.69	2.29	1.70	4.37	2.32	0.53	1.36	0.91
CO_2	.....	.....	.....	.....	0.72	.....	0.09	0.48	6.46	1.87	.....	0.51	0.06	.....	.....	.....	0.10	?	0.09	0.25	0.08	tr.	0.03
MnO	.....	.....	0.43	.....	0.20	0.09	0.16	0.13	0.22	0.17	.....	0.05	0.11	tr.	tr.	tr.	0.17	0.25	0.19	0.16	tr.	tr.	tr.
S.	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.03	tr.	0.04	tr.	tr.	0.02	tr.	tr.	tr.	tr.	tr.	.....
SO_3	.....	0.12	.....	0.19	0.04	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Cl	.....	0.03	.....	.....	tr.	0.03	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
MoO	.....	.....	.....	0.08	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
LiO	.....	.....	.....	.....	tr.	tr.	tr.	tr.	.....	.....	.....	tr.	?	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
V_2O_3	.....	.....	.....	.....	.....	.....	0.02	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Fe_2S_2	.....	.....	.....	.....	.....	.....	0.04	.....	0.54	0.02	.....	.....	.....	.....	.....	.....	.....	0.28	.....	.....	.....	.....	0.09
NiO,CoO	.....	.....	.....	.....	.....	.....	tr.	.....	0.03	.....	.....	0.13	0.03	.....	.....	.....	.....	tr.	0.03	tr.	.....	.....	.....
Cr_2O_3	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.58	0.48	0.15	tr.	.....	tr.	.....	.....	.....	0.06	.....	.....	.....
Total	100.20	100.03	100.41	99.95	100.14	100.45	100.17	99.96	100.15	100.96	99.77	100.13	99.16	99.78	99.70	99.96	99.55	100.25	99.18	100.22	100.31	100.22	100.03
Sp. gr.	2.80	2.86	2.89	2.95	2.70	2.77	2.79	2.68	2.91	2.80	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....

DESCRIPTION OF THE ROCKS ANALYZED, ALL FROM U. S. GEOLOGICAL SURVEY REPORTS.

Telluride Quadrangle.—No. 1, black vitrophyre from ridge east of pass between Marshall and Virginius basin. No. 2, monzonite from near lake NW. of San Miguel peak. No. 3, gabbro from Stony mountain. No. 4, gabbro-porphyry from pass south of Mount Sneffles.

La Plata Quadrangle.—No. 5, porphyry. No. 6, monzonite from Babcock peak. No. 7, monzonite facies of diorite mass. No. 8, diorite porphyry. No. 9, basic dike rock. No. 10, lamprophyre from Snowstorm peak.

Port Orford Quadrangle.—No. 11, serpentine, 12 miles north of mouth of Boulder creek. No. 12, serpentine, Iron mountain crest, near middle. No. 13, gabbro, SE. slope of Panther mountain. No. 14, gabbro, summit of Bald mountain. No. 15, gabbro, Brush creek 1.5 miles SE. Bald mountain. No. 16, gabbro, SE. ¼ sec. 7, T 343, R 142 on cross-road. No. 17, gabbro, left bank Rogue river, 2 miles below the mouth of the Illinois. No. 18, basalt, Cedar creek, 1.5 miles NE. Ophir. No. 19, basalt, near fork of West Bend trail, 2.5 miles south of Johnson creek. No. 20, basalt, Saw-tooth rock. No. 21, dacite-porphyry, 6 miles west of Big Bend of Rogue river. No. 22, dacite-porphyry, head of Boulder creek. No. 23, dacite-porphyry, south slope of Bald mountain.

TABLE II.—*Analyses of Spring-Waters.*

Parts in one thousand.

No.	1	2	3	4	5	6	7	8	9	10	11	12
Na	0.1042	0.7743	0.3554	0.3040	0.6116	.....	.....	.....	.....	.....	0.0310	0.0020
K	tr.	0.0669	0.0191	0.0094	0.0630	.....	.....	.....	.....	0.1285	0.0372	0.0128
Ca	0.5060	0.0305	0.0367	0.0121	0.0589	.....	.....	.....	.....	1.0739	.....	0.0012
Mg	.....	0.0010	0.0034	0.0004	0.0604	.....	.....	.....	.....	0.2352	.....	.....
Ba	.....	.....	.....	.....	.....	.....	.....	.....	.....	tr.	.....	.....
Sr	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Li	tr.	.....	.....	.....	.....	.....	.....	.....	.....	0.0003	.....	.....
Fe	tr.	.....	.....	.....	.....	.....	.....	.....	.....	0.0027	.....	.....
Mn	tr,	.....	.....	.....	.....	.....	.....	.....	.....	0.0009	.....	.....
Cl	tr.	0.9697	0.2396	0.2070	0.2272	0.9524	.....	.....	.....	4.2730	0.0480	.....
Br	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.0025	.....	.....
I	.....	.....	.....	.....	.....	.....	.....	.....	.....	tr.	.....	.....
Fl	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
CO_2	0.0852	.....	tr.	.....	0.5787	0.1776	0.2624	1.7513	.....	0.1792	0.0383	0.0089
SO_3	0.1614	0.3555	0.3901	0.3492	0.3131	0.1039	.....	.....	.....	2.0318	.....	0.0040
HPO_4	tr.	.....	.....	.....	.....	.....	.....	.....	tr.	0.0004	.....	0.0179
B_4O_7	.....	.....	.....	.....	.....	0.2174	1.8784	2.4043	tr.	tr.	.....	.....
Al_2O_3	tr.	0.0010	.....	.....	0.0018	0.0003	.....	.....	.....	0.0022	.....	0.0012
SiO_2	tr.	0.2788	0.1136	0.1310	0.1220	0.3106	0.0371	0.0418	0.2464	0.0080	.....	0.0317
H	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.0030	.....	.....
Organic	tr.	.....	.....	.....	.....	.....	0.0050	0.0076	.....	.....	.....	.....
O	.....	0.0194	0.0255	0.0080	0.0325	.....	.....	.....	.....	.....	.....	.....
H_2S	0.0500	.....	.....	.....	.....	0.0005	0.0045	0.0007	.....	.....	.....	.....
RHS and S	.....	.....	.....	.....	.....	0.0069	.....	.....	.....	.....	.....	.....
As_2O_5	.....	.....	.....	.....	.....	0.0036	.....	.....	.....	.....	.....	.....
SbO_3	.....	.....	.....	.....	.....	0.0005	.....	.....	.....	.....	.....	.....
P_2O_5	.....	.....	.....	.....	.....	0.0006	.....	.....	.....	.....	.....	.....
HgS	.....	.....	.....	.....	.....	tr.	.....	.....	.....	.....	.....	.....
FeO	.....	.....	.....	.....	.....	0.0002	.....	.....	.....	.....	.....	.....
MgO	.....	.....	.....	.....	.....	0.0005	.....	.....	.....	.....	.....	.....
Na_2O	.....	.....	.....	.....	.....	0.9193	.....	.....	.....	.....	.....	.....
CaO	.....	.....	.....	.....	.....	0.0005	.....	.....	.....	.....	.....	.....
K_2O	.....	.....	.....	.....	.....	0.1246	.....	.....	.....	.....	.....	.....
$FeCO_3$	.....	.....	.....	.....	.....	.....	.....	0.0010	tr.	2.0398	.....	0.0109
NaCl	.....	.....	.....	.....	.....	.....	1.1027	1.0397	13.6226	.....	.....	0.0243
Alk. Carb	.....	.....	.....	.....	.....	.....	2.0075	0.3809	0.4768	.....	0.0154	.....
KSO_4	.....	.....	.....	.....	.....	.....	.....	.....	0.3005	.....	.....	.....
$CaSO_4$	.....	.....	.....	.....	.....	.....	0.0234	.....	1.1548	.....	.....	.....
$NaSO_4$	.....	.....	.....	.....	.....	.....	.....	0.6890	.....	.....	.....	.....
MgCl	.....	.....	.....	.....	.....	.....	.....	.....	0.1637	.....	.....	.....
KCl	.....	.....	.....	.....	.....	.....	0.0470	0.0747	.....	.....	.....	.....
NaBr	.....	.....	.....	.....	.....	.....	.....	.....	0.0704	.....	.....	.....
Total	0.9068	2.5171	1.1834	1.0211	2.0692	2.8194	5.3675	6.3910	16.0352	9.9814	0.1699	0.1149

SPRINGS.

No. 1, Sulphur springs, Los Angeles; *Annual Report U. S. Geological Survey*, p. 195, 1876. No. 2, Hot spring at Hot Spring station, C. P. R. R.; *Chamberlin and Salisbury's Geology*, pp. 224–225. No. 3, Hot springs at the base of the Granite mountains, Nevada; *Chamberlin and Salisbury's Geology*, pp. 224-225. No. 4, Boiling spring at Honey Lake valley, California; *Chamberlin and Salisbury's Geology*, pp. 224–225. No. 5, Warm spring, Mono basin, California; *Bulletin No. 9, U. S. Geological Survey*, p. 27. No. 6, Steamboat springs, Nevada; G. F. Becker, *Geology of the Quicksilver Deposits of the Pacific Slope; Monograph* xiii. *U. S. Geological Survey*, p. 347. No. 7 and No. 8, two different shafts at Sulphur Bank, California; G. F. Becker, *Geology of the Quicksilver Deposits of the Pacific Slope; Monograph* xiii, *U. S. Geological Survey*, p. 259. No. 9, Glenwood springs, Colorado; *Glenwood Springs Hotel Pamphlet*. No. 10, artesian well at Sheboygan, Wisconsin; C. F. Chandler, *American Chemist*, p. 370, 1876. No. 11, the Mississippi river; W. J. Jones, *Report Louisiana State Board of Health*, p. 370, 1882. No. 12, the Sacramento river; W. J. Jones, *Report California State Board of Health*, 1878.

Table I. contains analyses of 23 eruptive rocks, and Table II. the analyses of 12 spring-waters, the first nine of the latter being hot springs, the tenth an artesian well, and the eleventh and twelfth river-waters. The rock analyses, which are from representative surface eruptives, show that these rocks must be very lean indeed in the useful metals. Mr. Waldemar Lindgren[7] mentions the finding of traces of pyrite, chalcopyrite and galena in the gray gneiss of Freiberg. Prof. Kemp mentions the finding of various metals in various eruptive rocks, but does not give any quantitative analyses.[8]

Don was unable to find any gold at all in the rocks he examined except in association with iron pyrites, which latter gave evidence of being the result of vein-making agencies. Of course, it may be said that all the analyses of the eruptive rocks are made after they have been leached out. If it could be shown that the surface eruptive rocks have a tendency to throw off metals, as they do steam and sulphur, during the cooling process this would remove many of my objections to considering them the source of the metals in our ore-bodies. In the lack of such proof, however, we must recognize that they are extremely lean, and therefore a very unlikely source of mineral wealth.

Of the four rocks from the Telluride quadrangle only one shows manganese; yet rhodonite and rhodocrosite are very common to the veins of this district. Of the six analyses from the La Plata quadrangle, every one shows manganese; yet it has been my observation that manganese is a rare constituent of the veins of this quadrangle. In the 13 analyses of rock from the Port Orford quadrangle a wide range of minerals is seen, which often are found in veins, yet the veins of this locality contain little but quartz, pyrite, chalcopyrite and gold.[9]

The table of spring-waters was rather surprising to me in that it shows that an artesian well-water may contain as much mineral matter in solution as the average hot spring. I do not see that a comparison of the minerals found in hot springs with those minerals found in the eruptive rocks is very instructive. Unfortunately, I have no complete analyses of all the rocks im-

[7] Metasomatic Processes in Fissure-Veins, *Trans.*, xxx., 659 *et seq.* (1900).

[8] The Rôle of the Igneous Rocks in the Formation of Veins, *Genesis of Ore-Deposits*, pp. 681 to 709, and *Trans.*, xxxi., 169 to 198 (1901.)

[9] *Port Orford Folio, U. S. Geological Survey.*

mediately surrounding a hot spring. If such analyses were available they would be very instructive. As it is, the only distinguishing characteristic of hot springs brought out by the analyses is the presence of sulphur and sulphur gases and of chlorine combinations. Fresh lava, we know, gives off fumes of sulphur and chlorine; hence it is natural to connect hot sulphur springs with fresh eruptives.

The analyses given in Table I. show very few of the useful metals in solution, but Posepny in his *Genesis of Ore-Deposits* mentions that lead occurs in the springs of Rippoldsau (according to Will, 1.6 to 3.7 mg. per ton), and in the Kissingen spring (13 mg. per ton), and quotes from G. Bischof, as follows, the maxima found in mineral springs up to 1854, in milligrams per ton of water:[10] Arsenious acid, 1.5; antimony oxide, 0.1; zinc oxide (sulphate), 13.3; lead oxide, 0.1; copper oxide, 6.4; tin oxide, 0.1.

It is not mentioned whether or not any of these may have been enriched in a secondary way. It would not, however, be surprising if no spring among those analyzed had been primarily enriched with useful metals. We have only a few analyses; ore-bodies are very rare things, and give evidence of having been made in comparatively short periods, while veins are very common things; so that, granted the hot springs are making veins, the probabilities are that they are nearly all making barren veins or barren parts of veins. Posepny found that the Sulphur Bank spring, whose enrichment is probably primary, carried small quantities of mercurial sulphide in suspension. At least he found this material on his filter-paper after filtering the water, but he found only a trace of mercury in the water. Unless we accept this case, I have not read of any in which a mineral spring has been "caught in the act" of making an ore-body, and this only emphasizes my belief that ore-bodies are formed in relatively short periods of time. Ore-bodies seem to have been formed in every geological age since early Palæozoic times; and if we grant that each mineralized district was enriched in a relatively short period, it would not be strange if very few ore-bodies, or none at all, were in process of formation at the present moment.

[10] *Genesis of Ore-Deposits*, p. 47.

We know that many veins are now in process of formation; and we find that many springs carry in solution the materials found in veins, showing that nature is prodigal in her methods. Probably a small part only of the vein-making contents of any spring is deposited in the underground channel; the rest "goes down the creek." If we should find a mineral spring in the process of forming an ore-body, we might expect most of the metallic constituents of the solution to have remained in it after it issued from the ground.

It is true that we analyze spring-waters after they have passed through the zone of precipitation; and it is conceivable that a water showing at the surface no trace of metal may have carried material quantities of metal before it reached the zone of precipitation. But in that case the water must have been completely robbed of metal-values in the zone of precipitation; and it is hard to understand how such a clean precipitation could be effected by such precipitating-agents as we attribute to the superficial zone. It is easier to believe that we have not as yet found an ore-body forming or a spring engaged in forming one.

It has been asserted lately that the curative effect of some mineral springs is largely due to radio-activity. Nearly all the radio-active metals are of high specific gravity; so that the association of mineral springs with ore-bodies or with magmas rich in heavy metals is further indicated in this way.

Glenwood springs, Colorado, and Hot springs, Arkansas, have both been found to be slightly radio-active. But the springs most remarkable in this respect hitherto discovered are the Doughty springs, in Delta county, Colo. Dr. Wm. P. Headden has made some very fine radiographs from the sinter surrounding these springs.[11]

There are several springs, and the analyses differ somewhat; but the principal radio-active spring (called the Drinking spring) has the following analysis, in parts per 1,000: Na, 0.045863; K, 0.001576; Li, 0.000446; NH_4, 0.000068; Ca, 0.005272; Ba, 0.000192; Sr, 0.000150; Mg, 0.003230; Fe, 0.000026; Al, 0.000054; Mn, 0.000060; Zn, trace; Cl, 0.019762; Br, 0.000065; I, trace; SO_4, 0.013022; SiO_2, 0.000696; BO_2, 0.000174; total, 0.090656.

[11] *Proceedings Colorado Scientific Society*, vol. viii., pp. 1 to 30 (1905).

These are not hot springs; and whether or not they are springs of primary enrichment is not clearly shown. It will be noted from the analysis that Na, Cl, and SO_4 are the principal substances found in solution; but the distinguishing feature of the spring is the barium sulphate which the water is actively precipitating on the mound around the spring. Dr. Headden says: "The deposition of practically pure baric sulphate by a mineral spring is, so far as I have been able to find, a unique fact."[12] The radium is intimately associated with the barium sulphate.

III. The Solutions Derived Their Metal-Values from a Comparatively Rich Source.

This follows necessarily, if it be admitted that ore-bodies give unmistakable evidence that they were formed by rich solutions. If we believe that the source of the values was the surface-rocks, but admit that "expiring vulcanism" set matters in motion for vein-making, we should expect all veins to show a certain amount of concentration of mineral values; at least all of the veins in the vicinity of eruptive rocks. But the complete barrenness of most veins, even in mining districts, is one of the hard facts that are pressed home upon every experienced mining man. There are also, of course, countless absolutely barren veins and dislocations outside the mining districts.

Some writers suppose that the surface eruptive rocks carry appreciably more mineral than other rocks, and that they are the source of the mineral in the ore-deposits. It is, however, a common observation that the characteristic eruptive rocks of a mining camp are not confined to the mineralized area. As examples, I will mention Cripple Creek, Colo., The Homestake, S. D., Kalgoorlie, W. A., Monte Christo, Wash., Goldfield, Nev., Arizona King, Ariz., and El Trinidad, Sonora. It is also common that these rocks carry either no values at all or a metal that is not characteristic of the camp. In the analyses given in Table I. it will be noticed that the eruptives of the La Plata quadrangle all carry manganese, while only one of those in the Telluride quadrangle carries manganese. Rhodocrosite and rhodonite are very prevalent in the Telluride quadrangle, but only occasionally met with in the La Platas, if my own

[12] *Proceedings Colorado Scientific Society*, vol. viii., p. 26 (1905).

limited observations are to be relied upon. I think that all this points to the exceptional and unusual sources for such ore-bodies.

The principal objection to a deep-seated and rich source for the mineralization of veins which I have read is that of Van Hise, who, calling attention to the limits of the zone of fracture, says:[13]

"On the assumptions (a) that the strength of the rocks is the same as at the surface, (b) that the rocks are all of the same kind, (c) that the temperature is the same as at the surface, (d) that the water present does not make any difference in the character of deformation, (e) that the rocks yield as readily by fracture as by flowage, (f) that the rocks break as readily by fracture when the deformation is slow as when it is rapid, and (g) that the rocks are among the strongest, I have calculated that the maximum depth of the upper part of the zone of flowage under mass-static conditions can not be greater than 12,000 meters."

He concludes that the practical limit in depth of the zone of fracture is about 5,000 m., and that a fissure would close almost at once at a depth of 12,000 meters.

The resistance of a large number of rocks to binding and crushing has been determined; but such figures give us no satisfactory basis for the calculation here involved. It is necessary to consider also the "arching" of any material, even of crushed material. Loose coke and ore have no strength whatever to resist flexure, yet they will "bridge" a blast-furnace, and broken ore will often arch in an ore-chute and choke it up.

If Prof. Van Hise's conclusion is correct, why does not rock-flowage prevent the continued existence of mountain-peaks 5,000 m. high, and of springs at the base of such masses?[14] If a fissure could not exist at a given depth, how can a peak exist to an equal height? Such a peak may represent the foot-wall of a rather flat fissure, the opposite side of which has been removed. Would the absence of the opposite side prevent the action of rock-flowage? Has the phenomenon of rock-flowage ever been observed, bulging out the solid rock at the base of a peak or precipice?

If a spring can flow from under a mass of rock 20,000 ft. high, why could not a fissure exist 20,000 ft. below the surface?

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[13] A Treatise on Metamorphism, *Monograph* xlvii., *U. S. Geological Survey*, p. 189 (1904).

[14] According to Mr. M. W. Conway's *Climbing and Exploration in the Karakoram-Himalayas* (vol. i., p. 486, 1894), Peak K2 of that range is 28,000 ft. above sea-level, and many other peaks exceed 20,000 ft. In Bolivia there are mountains rising somewhat abruptly 21,000 or 22,000 ft. from sea-level. Many other instances could be cited, from British Columbia and Alaska.

Again, the effect of rock-flowage, whatever it may be, is admittedly slow, and must be subject to arrest or diversion by the greater force of rock-movements in mass. Such movements, indicated in innumerable instances by their geological effects, are continually presented for our observation in non-volcanic earthquakes, like those at Charleston, San Francisco, Jamaica, etc., and are reported daily by the seismometers of the world. Is it reasonable to believe that a movement felt at a horizontal distance of 10,000 miles has had no effect below the depth of 5,000 or 12,000 m. (3 or 7 miles)? If it has had such effect, it must have counteracted the previous work of rock-flowage, and opened new fissures, upon which that slow agency must commence operations *de novo*.

Very recent seismometric observations (preceding by a few weeks the Jamaica earthquake of January, 1907) reported a submarine earthquake in the deepest part of the Pacific, far exceeding in intensity and energy anything hitherto observed on land. Such earthquakes occur under, say, 24,000 ft. of sea-water (the maximum depth off the coast of Asia is greater than that), equivalent in weight to 10,000 ft. of rock; yet they not only break the sea-bottom, but possess surplus energy enough to lift the sea itself, producing enormous tidal waves. May we not safely conclude that they might still occur under a greater superincumbent pressure, and, in particular, that 15,000 or 20,000 ft. of rock, the pressure of which, producing rock-flowage, operates much more slowly than an equal pressure producing water-flowage, would not necessarily prevent an earthquake sufficient to make and, for a time at least, maintain fissures?[15]

Again, it is not proved that the pressure which would close an open crack by rock-flowage would be sufficient to change the density of the rock itself, and close all pores and capillary passages in it. On the contrary, it is probable that the slow deformation of rocks under pressure takes place without fracture or change of density. This, at least, is indicated by the early experiments of Sorby and others, and by the actual observed conditions of limestone, etc., which have been thus changed in form, yet show their original structure. It follows, apparently, that the assumed lower limit of rock-flowage is not necessarily the limit of rock permeability, and also that any interruption

[15] This consideration was suggested to me in a private communication by the Secretary of the Institute.

of the closing of a fissure by rock-flowage might continue for an indefinite period, or until rock-flowage in new directions, or a forced change in the density of the rock, had completed the process thus interrupted. This leaves room for the hypothesis here advanced, which requires, not the endless persistence, but only the existence for a sufficient period, of deep channels of circulation.

Now, there is here no question of an absolutely open fissure, with walls nowhere in contact. On the contrary, fissures are almost always formed by movements of one wall relatively to the other, and are almost always "closed" to a certain extent by the "misfit" contact of the walls in their new relative position. This leaves more or less continuous and connected channels for underground waters and gases, the further closing of which by the pressure of the inclosing rocks may be long delayed by the fact that the pressure tending to close the openings must overcome the resistance of the solid masses which are keeping them open and the "arching" of the material around such openings. It must be admitted that the complete "squeezing out" of all such residual and interstitial cavities is likely to be a much slower process than the closing of altogether open and continuous fissures.

In view of the foregoing considerations, I can see no reason why small open channels may not exist as far below the surface of the earth as mountain peaks extend above the average gravity-level; and, moreover, as these channels would doubtless be filled with water, a practically incompressible liquid, having material weight of its own, I think we may conclude that they would resist closing all the more on that account, and, indeed, could not be completely closed, unless the water were provided with the means of escape—in other words, with channels!

Prof. Van Hise calls attention to the fact that at a certain depth the critical temperature of water (360° C.) would be reached, and that it could not exist as water below that depth. But it does not follow that the form in which it could exist would not possess equal density and solvent power.

According to the rate of increase assumed by many writers—1° C. for every 30 m. of added depth—the critical temperature would be reached at 10,350 m., if 15° C. be taken as the temperature of the surface. But we are scarcely warranted in as-

suming that rate as uniform to great depths. M. Walferdin, by a series of careful observations in two shafts at Creuzot, proved that down to a depth of 1,800 ft. the increase in temperature amounted to 1° F. for every 55 ft. of descent; but below the depth named the rate of increase was as great as 1° F. for every 44 ft. On the other hand, in the great boring of Grenelle, at Paris, the increase in temperature down to 740 ft. was 1° F. for every 50 ft.; but from 740 to 1,600 ft. it diminished to 1° F. for every 75 ft. A similar remarkable fact was shown in the Sperenberg boring, near Berlin, where the rate of increase for 1,900 ft. was 1° F. for every 55 ft., and for the next 2,000 ft. only 1° F. for every 62 ft. In the deep well at Buda Pesth there was actually found a decline in temperature below the depth of 3,000 ft.

A list of 164 wells, from 400 to 2,220 ft. deep, bored in the United States,[16] shows irregularities of temperature not to be referred to any general formula. To the rule mentioned above—namely, 1° C. for every 30 m. of added depth—there are far more exceptions than confirmations. No doubt these variations are due to local physical or chemical causes; and, in like manner, it must be conceded that under conditions of expiring vulcanism very high temperatures may prevail, probably even beyond the critical temperature of water. But it seems unsafe to reckon upon a transcendently hot interior of the mass of the earth.

Finally, it is not safe to assume that this mass is under such pressure as to be precluded from all movement whatever below a few thousand feet of its 4,000 miles of radius; and a movement causing displacement would give opportunity for the rise of a heavy magma to a higher level.

In view of the above considerations, I find nothing precluding the idea that the solutions which have formed ore-bodies have had comparatively rich sources, and that these sources were very likely laccolites of heavy magmas, brought up from the barysphere into the lower part of the zone of fracture.

IV. There is a Barysphere Containing Large Amounts of the Useful Metals.

This, I think, has never been seriously questioned. Physicists and astronomers have weighed the earth and found it not

[16] *Water Supply and Irrigation Paper* No. 149, *U. S. Geological Survey* (1905).

"wanting," but over-weight. R. von Sternbeck determined the specific gravity of the earth to be 5.6, while the average density of the surface-rock is 2.5. Chamberlin and Salisbury in their treatise on geology give the specific gravity of the earth as 5.57, and that of the lithosphere as 2.7. There is a theory that the greater relative weight of the earth is caused by pressure alone; that the material is the same throughout, but that the pressure has made the interior rocks more dense. I believe it has been demonstrated that rocks do yield somewhat to such pressure as may be artificially applied; but such evidence comes far short of the proof here required. To satisfy this theory it would be necessary for the rocks to be compressed, near the center of the earth, to one-fourth their volume at the surface. Against this hypothesis, we have the facts that magmas of very different specific gravity issue from the interior of the earth, and that eruptive rocks, as a class, are heavier than surface-rocks.

Van Hise remarks:[17]

"It is noticeable in the altered rocks that in proportion as deep-seated metamorphism is advanced the heavier (of the above) minerals appear."

V. Eruptions Spring from Various Depths and Bring Various Kinds of Magma Toward the Surface.

This seems to me to be shown by what is known of eruptions. As vents filled with molten material would not be subject to the causes limiting the depths of water-channels there is no limit to the depths to which we may expect them to extend. I understand that the majority of both astronomers and geologists regard the earth's interior as solid and rigid as steel. Eruptions are generally considered to be the result of local stress and friction. Just what is the cause of the stress and just how the force is applied are matters of discussion. A very simple explanation, but one which does not seem to appeal to most writers, is that the axis of the earth is gradually shifting, and the earth being an oblate spheroid has to keep rearranging its mass to suit the new positions of the axis.

At Cananea, Sonora, in 1902, I saw an illustration of a volcano on a very small scale. A block of heavy iron gossan, constituting, roughly, a cube of about 200 ft. on a side, or 8,000,-

[17] A Treatise on Metamorphism, *Monograph* xlvii., *U. S. Geological Survey*, p. 183 (1904).

000 cu. ft. in volume, had been undermined, and slipped down 6 ft., crushing the timbers. The heat produced underground, near the foot-wall, was intense, and on the surface two or three small jets of steam appeared. If a little block of ground like that, slipping 6 ft., could generate sufficient heat to produce such jets of steam, it is easy to understand how the movements of a large region might incidentally produce a volcano or two. Suppose, for example, that an eruption is caused by a force which produces faulting under great pressure. The first effect may be confined to the lithosphere, so that barren magmas are squeezed out. But, as the force gathers intensity, the fault extends into the barysphere, and some of the latter is forced upward, crowding out the lighter lavas above it. By reason of its greater specific gravity it floats the lighter rocks above it, and forms, within the reach of underground waters, a laccolite, which may subsequently become the source of valuable mineral deposits.

Chester Wells Purington, in the Telluride Folio of the U. S. Geological Survey, says, in effect, that the basic parts of eruptive rocks, such as hornblende, augite, biotite, contain more of the useful metals than the other parts, and deems it probable that the mother magma had a basic portion, which might be the source of the metals in the ore-deposits. His idea and mine are not widely at variance.

VI. Only Those Eruptions which Disturb the Barysphere and Bring a Magma Rich in Metals Sufficiently Near the Surface to be Leached by Vein-Making Solutions are Productive of Valuable Ore-Deposits, Other Eruptions Producing Barren Veins.

In support of this proposition there are many indications not mentioned above. In many mining districts there have been successive eruptions, but the ore-bodies are definitely associated with one eruption and appear to have no relationship with the others. Thus, at Butte, Mont., the ore-bodies are associated with a quartz-porphyry eruption, while the acid granite, basic granite and rhyolite eruptions produced no ore-bodies. At Cripple Creek we have a whole series of eruptions; but the mineralization of the veins followed on the heels of the nepheline-basalt eruption.

We often find in a mining district several series of veins, only one of which bears mineral values. At Rico, Colo., for instance, there is a series, terminating at the so-called "contact," which has been enriched with silver and other metals; and there is another series of strong quartz-veins not thus enriched. These facts suggest that, among the eruptions, one must have been radically different from the others. Yet analyses of the surface-rocks do not reveal any startling differences. It seems evident that the mineralized series of veins must have been formed from a source radically different from that of the barren ones. My explanation is, that in a series of eruptions, one may have been sufficiently deep-seated to disturb the barysphere and force some of its material toward the surface. It would never reach the surface, because its specific gravity would cause it to form, sooner or later, a laccolite, floating the surface-rocks. But, in exceptional cases, it might rise far enough to become subject to the agencies which make mineral-bearing veins.

I presume that the barysphere includes different kinds of unsegregated magmas. It may be built up concentrically, or it may be simply spotted, as the surface is, with different rocks. A laccolite of magma rich in copper might give rise to a surface region yielding copper; one rich in gold might become the origin of a gold-bearing district, etc.

I do not mean that the constituents of the magma would govern entirely. It is conceivable that conditions of the solution and precipitation of the metals might also be influential. But this general hypothesis suggests an explanation of those cases in which totally different kinds of ore-deposits occur in the same surface-rocks, close together, and under conditions apparently similar, except as to age. Butte, Rico and Leadville are cases in point. At Butte there is a great mass of dark, basic granite, which contains two vein-systems. In the southern part of the camp are the famous veins of copper, containing sulphide ore-bodies with more or less quartz. The northern system produces ores of silver, lead, zinc and iron. Prof. Kemp has called attention to the fact that the northern ores are abundantly associated with manganese minerals, especially rhodonite; that no manganese occurs in the copper belt and no copper in the silver belt; and infers that "such results could originate only in different deep-seated sources."

This hypothesis offers also an explanation of cases in which there is an extensive surface-area, showing similar eruptive rocks throughout, yet only a small part of which has been mineralized. Thus, in areas like southern Nevada and the Yaqui River country of Sonora, there are vast quantities of eruptive rocks of much the same kinds, but only in isolated localities have paying veins been found. Sometimes these localities are, and sometimes they are not, characterized by a trifling exposure of a peculiar eruptive rock. In the former case, the trifling surface manifestation seems utterly inadequate to account for the very exceptional vein-contents of the localities.

Cripple Creek is another case in point. The whole Arkansas plateau is prolific of all the rocks characteristic of Cripple Creek (unless, it may be, the basalt dikes). The largest masses of phonolite I know of are found, as in Grouse mountain and Little Pisgah peak, outside the productive area, while around Saddle mountain and at Bare hills there are large masses of andesitic breccia, yet no ore-deposits. At Globe, Ariz., there is an extensive area, northwest of the camp, that has the same formation as that surrounding the mines; but thus far no ore-deposits of value have been found in it, though it is not lacking in veins.

Of Grass valley, Cal., the U. S. Geological Survey folio says: "The veins occur in almost any one of the many rocks making up the bed-rock series. Excellent mines are located in the grano-diorite, diabase, slate and schists." Evidently the surface-eruptives did not govern in this case.

In the case of several eruptions, only one of which is associated with ore-bodies, the theory would be that the one associated with the ore-bodies was the deep-seated one, which brought some of the mineralized magma within reach of the vein-making agencies, and that, while the surface-manifestation may have been weak, and not different essentially from other eruptions in the same locality, the eruption in depth was radically different.

As to the series of veins in a given district, we would say that the barren ones were the products of the shallow eruptions, while the rich ones were the product of an eruption that brought a rich magma surface-ward. In the case of a large area of eruptive rocks containing a very small mineralized dis-

trict, it seems to me hard to understand why the mineralization is not much more general, if the surface eruptives are accountable for the metal-values. If, however, these values came from a relatively small buried mass of very richly mineralized eruptive rock, the restricted mineralized surface-area is at once explained.

Again, there are occasional mining districts in which no eruptive rocks at all appear on the surface, such as the zinc-lead deposits of southwestern Illinois, and the Otago gold-fields of the South Island of New Zealand. (The latter are described by Rickard in his discussion of Posepny's *Genesis of Ore-Deposits.*) In such cases the influence of a richly mineralized underlying laccolite is highly reasonable.

No. 27 A.

The Formation and Enrichment of Ore-Bearing Veins.

SUPPLEMENTARY PAPER.

BY GEORGE J. BANCROFT, DENVER, COLO.

(Spokane Meeting, September, 1909. *Trans.*, xl., 809.)

At the New York meeting of the Institute, April, 1907, I presented a paper entitled, The Formation and Enrichment of Ore-Bearing Veins,[1] in which paper I advanced the following propositions:

(1) That the majority of mineralized veins are the product of expiring vulcanism; (2) that most of these veins were primarily mineralized by comparatively rich solutions in comparatively short periods of time; (3) that the solutions gained their metal-values from a comparatively rich source; (4) that there is a barysphere containing large amounts of the useful metals; (5) that eruptions spring from various depths and bring various kinds of magmas towards the surface; and (6) that only those eruptions which disturb the barysphere and bring a magma rich in metals sufficiently near the surface to be leached by vein-making solutions are productive of valuable ore-deposits, other eruptions producing barren veins. Ore-deposits due to magmatic segregation were not included in this general survey.

As a result of considerable further study I have modified my views in some respects, while in others I feel more sure than ever of the ground taken at that time.

That ore-bodies are infrequent occurrences and born of extraordinary conditions I think is now generally accepted. The theory that persisted for a time—namely, that ore-bodies were formed by the ordinary ground-water, which consists of extremely dilute solutions, derived from leaching extremely lean surface-rocks, and which must occupy enormously long periods of time in concentrating the values so leached, is, I think, now pretty generally regarded as not applicable to the great majority

[1] P. 696, this volume.

of our mining-districts, although it may account for a few isolated deposits.

I note that a few recent writers still use this theory as a sort of "point of departure" for their discussions, but the majority seem to realize that the tendency of ordinary ground-water circulation is to diffuse any soluble matter rather than to concentrate it, and that an unusual precipitant must be present to provoke an important concentration under this hypothesis.

That the forces of expiring vulcanism are the agencies which account most logically for ore-bodies is an opinion very generally held, not only because of the intimate association of ore-bodies with eruptive rocks, but also because the study of active volcanoes and of the springs rising near them shows that ore-making agencies to a limited extent, at least, are at work there. Thus, A. Lacroix[2] found pyrite, pyrrhotite, and galena, together with sulphates of sodium, potassium, calcium, magnesium, and aluminum, in the sublimates of fumaroles on Vesuvius; J. W. Mallet[3] discovered silver in volcanic ash at Cotopaxi and Tunguragua; O. Silvestri[4] found copper in the fumes of Etna, while traces of practically all the common metals have been found in eruptive rocks.

Similarly, it has been recognized that the period of expiring vulcanism could not have been of very long duration, geologically speaking, although it has been shown that in some districts the repeated recurrence of eruptive action has had the effect of continuing the mineralizing action through long periods of time.

My fifth and sixth propositions have not been so well established. I think it is generally admitted that certain eruptive rocks produce mineralized areas, while others do not; this suggests most forcibly that the eruptives themselves differed very decidedly in the matter of mineral content; and it seems reasonable to infer that those eruptives which do produce mineral richness have been rich themselves and probably originated at great depth. The advance of science has still further substan-

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[2] *Bulletin de la Société Française de Minéralogie*, vol. xxx., p. 219 (1907).

[3] *Proceedings of the Royal Society*, vol. xlii., p. 1 (1887); vol. xlvii., p. 277 (1889–90).

[4] *I Fenomeni Vulcanici presentati dell' Etna, etc.* (Catania, 1867), per *Bulletin* No. 330, *U. S. Geological Survey*, p. 217 (1908).

tiated the theory that the earth has a very heavy center, and it is reasonable to suppose that this increased specific gravity is partly due to relatively large metal-content. It is not, however, generally conceded that it is necessary for a mineralizing eruptive to be so rich in metals and so heavy that it would rarely or never reach the surface, but would form laccolites, according to my old hypothesis. Nor do I longer hold this view. At that time I remarked:

"If it could be shown that the surface eruptive rocks have a tendency to throw off metals, as they do steam and sulphur, during the cooling process this would remove many of my objections to considering them the source of the metals in our ore-bodies. In the lack of such proof, however, we must recognize that they are extremely lean, and therefore a very unlikely source of mineral wealth."

Now, I think there are very good reasons for believing that this very thing is true—namely, that eruptive rocks do have a tendency to throw off their metal-content during the cooling process, or, rather, as soon as they reach a horizon of lessened pressure, which condition is apt to be coincident with cooling.

The wonderful crystallographic researches of J. E. Spurr, Waldemar Lindgren, and others, have shown that magmas are totally different from dry melts, and the cooling of a magma is accompanied by a remarkable series of differentiations. Mr. Spurr has shown how the metals would be concentrated either in a very base or a very acid magma, and finally, in the case of the acid magma, would be extruded together with pure silica and water, thereby forming veins. I think, however, that those who have made a great deal of the powerful agency of magmatic differentiation have overlooked a very active contemporary agent—namely, chlorine. Bromine, iodine, and fluorine may be equally active agencies in volcanic emanations; but as these elements are relatively rare, I shall confine myself here to the very active part which chlorine may play in carrying away from the hot eruptive its metal-content and depositing the same in ore-bodies. These considerations have been suggested to me by studying the dry-chlorination process for the treatment of complex ores, as developed by J. L. Malm, at Corbin, Mont., and at Denver, Colo. This process depends primarily upon the facts that, in the dry state, chlorine has a greater affinity for the metals than sulphur or oxygen, and that the chlorides of all the metals are soluble together in hot water.

Thus, cupric chloride, lead chloride, zinc chloride, gold chloride, and iron chloride are soluble in hot water direct, and silver chloride is soluble in hot cupric chloride.

Now, it is noticeable that chlorine is nearly always present in volcanic emanations. Thus, J. W. Judd says:[5]

"The most abundant of the substances which are ejected from volcanoes is steam or water-gas, which, as we have seen, issues in prodigious quantities during every eruption. But with the steam a great number of other volatile materials frequently make their appearance. The chief among these are the acid gases known as hydrochloric acid, sulphurous acid, sulphuretted hydrogen, carbonic acid, and boracic acid; and with these acid gases there issue hydrogen, nitrogen, ammonia, the volatile metals arsenic, antimony, and mercury, and some other substances."

After dwelling upon the large amount of CO_2 present in volcanic gases, Chamberlin and Salisbury have the following to say with reference to emanations:[6]

"Sulphur gases are very common accompaniments of volcanic eruptions. They take the forms of sulphuretted hydrogen and sulphurous acid and perhaps of sublimated sulphur, all of which are liable to pass by oxidation and hydration into sulphuric acid. Chlorine and hydrochloric gases are also common, particularly at high temperatures. Fluorine and other gases are occasionally present."

T. Wolf found that near the crater of Cotopaxi the fumes were mostly of hydrochloric acid with some free chlorine, while at lower levels hydrogen sulphide was found with a trace of sulphur dioxide.[7]

Sainte-Claire Deville found chlorides of iron and copper in a fumarole of Vesuvius.[8]

R. Bunsen found various metallic chlorides in the sublimates around fumaroles of Mt. Hecla in Iceland.[9]

A characteristic of volcanic emanations is, that chlorine is found either free or as the chloride of the metals, or as hydrochloric acid, while a characteristic of hot mineral springs is that the water contains large quantities of the chlorides of sodium and potassium. Granting that such hot mineral springs

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[5] *Volcanoes: What They Are and What They Teach*, p. 40 (1881).

[6] *Geology*, 2d ed., vol. i., p. 619 (1906).

[7] *Neues Jahrbuch für Mineralogie, Geologie und Palaeontologie*, p. 163 (1878).

[8] *Bulletin de la Société Géologique de France*, Second Series, vol. xiii., p. 606 (1855–56).

[9] *Annales de Chimie et de Physique*, Third Series, vol. xxxviii., p. 215 (1853).

are related to eruptions, and that the chlorine in both emanations and springs had a common origin, it is evident that the part which has escaped by the medium of spring-water has undergone certain reactions, which the part which escaped as a hot gas, from an open vent, did not undergo. Does not this suggest what may take place in case the chlorides are extruded through crevices or veins where they may encounter gradually lessened temperatures together with water?

Now, it is known that the temperature of fluid magmas may range up to 3,000° F.[10]

Let us suppose that, under a temperature of 1,100° C., we had a magma which contained chlorine, water-gas, sulphur, silver, copper, lead, iron, zinc, and gold. Of course, there would also be other elements present, but, as previously stated, I shall not try to cover the whole field. Let us suppose that there is sufficient chlorine to form chlorides with all the metals and an excess besides. Any hydrogen present would be combined with the chlorine, the affinity for chlorine being greater than for sulphur. Now, let us try to imagine what would happen as this magma approached the surface.

At the temperature given, the chlorine would attack all the metals, except gold, and the chlorides would all be gases, for it is well known that the metallic chlorides are all volatile at relatively low temperatures.

The chloride of gold under atmospheric conditions decomposes at about 120° C. Of course, the volcanic gases are under some pressure even when escaping from the magma, and, as pressure raises the temperature of decomposition, it is difficult to say just how cool the magma must become before the gold would accompany the other metals.

The fact that gold is often found by itself in a state of great purity may be accounted for by its isolation from the other metals as regards chemical reactions. Thus, at Farcum Hill, Breckenridge, are found deposits of most beautiful crystalline gold by itself, while less than a mile away are large deposits of complex ores. The complex ores occur in the eruptive dikes or on the contacts, while the gold is found in carbonaceous shale. It is well known that carbon will precipitate gold from

[10] *Geology*, Chamberlin and Salisbury, 2d ed., vol. i., p. 615 (1906).

a chloride solution, as is done in wet-chlorination mills, but it will not precipitate the other chlorides.

The chlorine would not attack the silicates of the eruptive, as is shown by the experiments of Brun,[11] who heated a Lipari lava and observed the following exhalations:

From 0° to 825°, volatilization of water.

At 825°, first evolution of chloride vapors.

From 874° to 1,100°, temperature of explosions.

At 1,100°, mean temperature of flowing lava.

Although the dry-chlorination process does not use high temperatures, Mr. Malm has experimented with chlorine and the ordinary rock-minerals at high temperatures and has shown that they do not react.

The sulphur would occur as sulphur gas and partly as sulphur chloride. There would, of course, be a great deal of water-gas present. As the magma rose to a horizon of lessened pressure these gases would expand and leave the magma, bursting out through any veins or vents or porous strata that might provide a means of escape. The great distance to which the metals have penetrated porous strata, as, for instance, at Morenci, Ariz., may be accounted for in this way.

The farther from the magma the gases traveled the cooler they would become, and as they became cooler they would become a liquid. We would then have the chlorides of the metals in a hot aqueous solution, together with sulphur chloride and elemental sulphur, the latter in an extremely fine state of subdivision (as it is found in many mineral springs).

Precipitation would not take place till some precipitating-agent was encountered in the rocks.

The cooling of the solution would throw down the lead and the lead only. Silver chloride is difficultly soluble and easily precipitated. This may account for the exceeding purity of some lead-deposits and the frequent association of silver and lead.

If CaO in abundance were encountered all the metals would be precipitated together. This may account for the complex nature of many deposits in porphyry-lime contacts, as, for instance, at Leadville, Rico, Breckenridge, etc.

[11] *Archives des Sciences Physiques et Naturelles*, Fourth Series, vol. xix., pp. 439, 589 (1905).

It is fair to assume that the heated eruptive would drive off the CO_2 from any limestone in immediate contact with it. The chloride gases emanating from the same eruptive would find an immediate and abundant precipitant in the form of CaO thus formed, or, in case conditions became cool enough for water to convert the oxide to the hydroxide, the latter would be equally efficient as a precipitant. Thus,

$$2\,MCl_x + xCaO = M_2O_x + xCaCl_2$$
$$2\,MCl_x + xCaO + xH_2O = 2\,M\,(OH)_x + xCaCl_2.$$

In granitic or eruptive rocks, the methods of precipitation are not quite so simple. I have immersed pieces of Boulder County granite in solutions of the metallic chlorides, sulphur chloride, and a little free acid, and at the end of three days there was no appreciable result. Again, I have boiled pieces of the same granite in strong hydrochloric and sulphuric acid, and in half an hour the reactions were very considerable. The hydrochloric acid was the more active. The piece of granite was eaten away considerably. Examination of the remaining piece with a magnifying-glass showed that the surface was reduced to a covering of spongy silica and white mica. Whether the mica had been whitened by leaching the iron, or whether only those bits remained intact which had no iron, I am not prepared to say. In addition to the piece remaining undissolved (at the end of 30 min.), there was a sediment which, on examination, appeared to be rounded and porous pieces of silica and minute flakes of pure white mica. The test with sulphuric acid rendered the piece darker. Only a very small part went into solution. An examination with a glass has shown the feldspars to be lacking and the surface to be covered with a coating of pearly silica and black mica. In this connection Clarke says:[12]

"Hot waters, charged with sulphuric or hydrochloric acid, attack nearly all eruptive rocks, dissolve nearly all bases, and leave behind, in many cases, mere skeletons of silica."

On this subject Judd says:[13]

[12] *Bulletin No.* 330, *U. S. Geological Survey*, p. 408 (1908).
[13] *Volcanoes: What They Are and What They Teach*, p. 41 (1881).

"In many volcanoes the constant passage through the rocks of the various acid gases has caused nearly the whole of the iron, lime, and alkaline materials of the rocks to be converted into soluble compounds known as sulphates, chlorides, carbonates, and borates; and, on the removal of these by the rain, there remains a white, powdery substance, resembling chalk in outward appearance, but composed of almost pure silica. There are certain cases in which travelers have visited volcanic islands where chemical action of this kind has gone on to such an extent, that they have been led to describe the islands as composed entirely of chalk."

F. Henrich shares the same view, claiming that the chlorides of potassium and sodium found in sublimates of aqueous fumaroles were formed by the action of moisture and hydrochloric acid on the alkaline silicates of the heated lavas.[14]

We know from observation underground that granitic and other rocks are attacked by mineral solutions which produce first a softening of the rocks, and eventually remove all the original constituents except the silica and hydrous alumina silicates.

It is, of course, difficult to reproduce in the laboratory with a few simple salts the complex reactions that take place far underground; and here at least we must take the evidence as we find it, even if it is difficult to reproduce the reactions.

We find chlorine or hydrochloric acid or metallic chlorides issuing from volcanoes, and we find sodium, calcium, and potassium chlorides issuing from mineral springs; so it seems highly probable that the sodium and potassium silicates break up, and the chlorine, after it has become cooled below the boiling-point of water, reacts with the sodium or potassium, dropping any metals with which it may have been combined.

The reactions leading to the formation of calcium chloride have been explained above. The reactions with the silicates would most naturally begin with the free hydrochloric acid, thereby liberating hydrogen, which would combine with the sulphur to form H_2S, and this in turn would precipitate the metals according to the following reactions:

$$MCl_x + \frac{x}{2}H_2S = xHCl + MS_{\frac{x}{2}},$$

and would convert any metals already precipitated by other agencies to the sulphides, as follows:

[14] *Zeitschrift für angewandte Chemie*, vol. xix., No. 30, p. 1326 (July 27, 1906); vol. xx., No. 5, p. 179 (Feb. 1, 1907).

$$MO_x + xH_2S = MS_x + xH_2O$$
$$M + xH_2S = MS_x + xH_2.$$

The first reaction would result in more hydrochloric acid, which would be available to repeat the cycle.

Whether the metals are precipitated by CaO or by reactions with the silicates, they would be almost at once converted to sulphides, according to the above reactions; and that is the condition in which we find them. Gold, which is precipitated by carbon, would not be subject to the action of H_2S, and hence would likely occur as free gold in carbonaceous formations, which agrees with the facts as we find them.

As stated above, I have confined myself, for the sake of simplicity, to an arbitrarily-chosen condition. It is my purpose to point out the very active part which the halogens may play in divesting an eruptive of its metal-contents, and conveying the same into neighboring veins or openings in the rocks, rather than to prescribe the exact steps that are followed. It is conceivable that under certain conditions the above-mentioned reactions may be very important, while in others they may be negligible. It is conceivable that in some cases an eruptive may be totally divested of its useful metals and yet little of it be precipitated short of the atmosphere. This may account for the Snake river placer gold, which is extremely fine, and so often found associated with volcanic ash as to provoke the theory that it had an atmospheric origin. On the other hand, a metalliferous eruptive may be only partly relieved of its metal-content, the residue remaining in a more or less segregated form in the body of the eruptive, as at Ely, Nev., where the sedimentaries adjoining the eruptive area contain veins and deposits of copper-ore, while the eruptive itself contains large masses of low-grade ore which appear to be due to magmatic segregation.

I think these considerations, helping to explain some of the puzzling things about ore-bodies, may be of service in promoting progress towards the goal of a perfect understanding of the subject.

No. 28.

The Distribution of the Elements in Igneous Rocks.

BY HENRY S. WASHINGTON, NEW YORK, N. Y.

(Chattanooga Meeting, October, 1908. *Trans.*, xxxix., 735.)

I. Introduction.

During the last twenty years or so the chemical investigation of rocks has made great advances, and it is now generally recognized that a knowledge of the chemical composition is as essential as that of the texture or mineral composition—if not more so—for the proper classification of rocks and study of their origin and relationships. Rock-analyses have vastly increased in number and, what is of greater importance, in quality. New and improved methods permit of greater accuracy than was possible in the early days, and the list of chemical constituents frequently determined has risen from the seven or eight of the greater part of the nineteenth century, to twenty or more. Indeed, rock-analyses with determinations of so many constituents are now commonly made by the chemists of the United States and Australia, while in Germany, Great Britain, France, and Italy the rarer constituents are determined more frequently than formerly.

As a consequence of this modern, accurate work, it has been discovered that some elements which were formerly supposed to be rare are of wide-spread occurrence and are often present in considerable amount. The fact is further being developed that the elements tend to show certain relations of occurrence or abundance in connection with each other. This is a fact which is applicable to the rarer elements, and which also finds a broad geological and petrological expression in the recognition of petrographic provinces. We are beginning to obtain some definite, though as yet rudimentary, knowledge of the distribution of the elements among igneous rocks.

Some of the results along these lines obtained by study of the vast accumulation of analytical data now available are well known to petrologists, while others do not seem to be so gener-

ally understood. To the non-petrologist they are, naturally, mostly unknown, and, as the general principles involved, and, indeed, some of the specific instances, have a more or less important bearing on the occurrence and characters of certain deposits of metallic ores and other economically important minerals, a discussion of the subject may be of interest to mining engineers.

Indeed, to the observations and operations of mining engineers and mining interests generally, the petrologist is indebted and must look for some of his data. This is especially true of those relating to the precious metals and others of commercial importance, the amounts of which usually present in rocks are so small as almost or quite to defy detection by ordinary analytical methods, and whose presence is often revealed only through search for and the exploitation of localities where they have undergone concentration. It must be premised, however, that our knowledge is at present very uneven, allowing fairly safe and detailed generalizations as regards some of the elements, very rudimentary or general ones as regards others, and again allowing almost none at all.

II. General Chemical Composition of Igneous Rocks.

The first and most important fact to be noted of igneous rocks is that, with the exception of some rare ore-bodies due to the differentiation of igneous magmas, they are composed almost wholly of silica and silicates. The vast majority of igneous rocks are silicate rocks, in which silica forms the most prominent and the never-failing constituent. Most of the minerals which compose them are combinations of silica with various bases, and it is a striking fact that the number of minerals which go to make up the majority of igneous rocks, and which are most abundant and most often met with, is very small.

The proportions in which these minerals may be present vary very widely. Some rocks are known which are composed wholly, or practically so, of but one mineral. Combinations of two are not infrequent, while most rocks contain at least three, and usually many more, minerals and in the most widely diverse proportions. It follows, therefore, that the chemical composition of igneous rocks may vary within very

wide limits, as regards any or all of the chemical constituents; and that, furthermore, some rocks may be of very simple chemical composition, while others may be very complex, with many constituents present, since the minerals themselves may be either very simple or highly complex in chemical composition.

The most important chemical constituents (stated as oxides, in accordance with the usual custom) are as follows: silica, SiO_2; alumina, Al_2O_3; ferric oxide, Fe_2O_3; ferrous oxide, FeO; magnesia, MgO; lime, CaO; soda, Na_2O; potash, K_2O; and water, H_2O. Some or all of these major constituents, as they are termed, are invariably present, so far as known, and collectively they constitute about 98 per cent. of all known rocks. The chief oxides, from silica to potash inclusive, enter into the composition of the most important and most commonly occurring rock-forming minerals, as well as the glass of imperfectly crystallized rocks.

The rôle of water is somewhat different. It would seem to be universally present in the magma, and its presence (along with that of other substances) lowers the freezing-point and increases the tendency to crystallization of the liquid mass. Most of this water is lost if the magma reaches the surface and it appears in the enormous clouds which accompany volcanic eruptions and the steam of volcanic fumaroles; and much of it also escapes if the magma solidifies beneath the surface, giving rise to subterranean water-supplies, which are held by many to be an important factor in the formation of many ore-deposits. A small proportion of the water originally present may remain in the solidified rock in a combined form, as part of the more complex mineral molecules, those of pyroxenes, amphiboles, and micas, for instance; and some may also remain as inclusions of water in the minerals of intrusive rocks.

There are also almost invariably present in igneous rocks small amounts of titanium, phosphorus, and manganese, though these are often neglected and thus overlooked in the less complete analyses. Carbon dioxide is also met with, but its presence, as reported in analyses of igneous rocks, is almost invariably due to decomposition, and it cannot be usually regarded as an essential or original constituent of rocks.

In addition to these most important constituents, the refine-

ments and increasing completeness of modern rock-analysis show that many others are frequently present, often in scarcely more than traces, but again in very appreciable quantities. The most important of these minor elements are: zirconium, sulphur (as sulphides and as sulphur trioxide), chlorine, fluorine, vanadium, chromium, nickel, barium, strontium, and lithium. Exceptionally, others may be determined: as boron, cobalt, copper, gold, silver, molybdenum, the metals of the cerium and yttrium groups, nitrogen, and others. Indeed, as Dr. Hillebrand[1] says, "a sufficiently careful examination of these rocks would show them to contain all or nearly all the known elements, not necessarily all in a given rock, but many more than anyone has yet found." The researches of Sandberger, Stelzner, and Dieulafait also point to the same conclusion.

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TABLE I.—*Average Composition of Igneous Rocks.*

	I. United States, Clarke, 1904.	II. The World, Washington, 1903.	III. Complete Average, Clarke, 1904.		IV. Clarke, 1904.
SiO_2	60.48	57.78	59.87	O	47.09
Al_2O_3	15.17	15.67	15.02	Si	28.23
Fe_2O_3	2.61	3.31	2.58 +	Al	7.99
FeO	3.44	3.84	3.40 +	Fe	4.46
MgO	4.10	3.81	4.06	Ca	3.43
CaO	4.84	5.18	4.79	Na	2.53
Na_2O	3.43	3.88	3.39	Mg	2.46
K_2O	2.96	3.13	2.93	K	2.44
H_2O (110° +)	1.48	1.42	1.46	Ti	0.43
H_2O (110° —)	0.41	0.36	0.40	H	0.17
TiO_2	0.72	1.03	0.72	C	0.14 —
P_2O_5	0.26	0.37	0.26	P	0.11
MnO	0.10	0.22	0.10	S	0.11
CO_2	.....	.....	0.52 —	Ba	0.089
S	.....	.....	0.11	Mn	0.084
BaO	.....	.....	0.11	Cl	0.07 —
Cl	.....	.....	0.07	Sr	0.034
Cr_2O_3	.....	.....	0.05 —	Cr	0.034 —
SrO	.....	.....	0.04	Zr	0.026 —
ZrO_2	.....	.....	0.03 —	Ni	0.023 —
NiO	.....	.....	0.03 —	F	0.02 +
V_2O_3	.....	.....	0.03 —	V	0.02 —
F	.....	.....	0.02 +	Li	0.01
Li_2O	.....	.....	0.01		100.00
	100.00	100.00	100.00		

higher figure in I. may be ascribed in part, as pointed out by Clarke, to the inclusion of many separate silica-determinations, which were undertaken on rocks comparatively high in this constituent; in part to the inclusion in the estimate of some analyses of siliceous gneisses and schists, rocks which were not regarded in my estimate; and probably in part to the fact that in Clarke's estimate only rocks from the United States were considered. But notwithstanding the slight discrepancies and the uncertainty introduced by non-allowance for the disturbing factors mentioned above, the results of the two calculations are so concordant that we may feel a high degree of confidence in the belief that the data given here approximate closely to the average composition of the earth's accessible igneous rocks.

In column III. are given the results of a more complete estimate by Clarke, which includes the minor constituents frequently present in igneous rocks, but which are only deter-

mined in the more complete analyses, as those made by the chemists of the U. S. Geological Survey. It will be seen that the data are in agreement with the general composition of the most common rock-forming minerals, their constituents, silica, alumina, ferric and ferrous oxides, magnesia, lime, soda, potash, and water, making up 97.9 per cent.

The estimated amount of carbon dioxide is undoubtedly too high, and is due to the number of analyses of altered rocks which were included in the estimates.

We may examine the matter further and, resolving the oxides into their elementary components, ascertain the average amounts of the elements in the igneous crust of the earth. This problem has been studied by Clarke in the papers already cited, and by Vogt[3] in Norway. The results of Clarke's latest calculations are given in column IV. of Table I., the figures including those for the minor constituents of column III., just noticed. In an earlier computation Clarke introduced estimates of the elements which make up the air, the water of the oceans, and such non-igneous rocks as limestone and coal. But the introduction of these into the calculation does not materially alter the final results from those given here, in which they are omitted, since these bodies are of relatively very slight quantitative importance compared with the whole mass of known rocks, however large they may loom to our eyes. Ore-bodies also are quite negligible in this connection.

These data show that oxygen composes almost one-half, silicon more than one-quarter, and aluminum about one-twelfth of the earth's crust (the three together amounting to 83.3 per cent.), while iron, calcium, sodium, magnesium, potassium, and titanium follow after in the order named in decreasingly small amounts. Thus, only nine elements together constitute 99 per cent. of the igneous crust. This is certainly a very remarkable fact, and one doubtless of great significance for the proper understanding of the true constitution of our globe, could we but interpret it aright, as some day we may hope to do.

The relatively high position occupied by titanium, ninth on the list in the order of abundance, is also a striking feature, as this element is commonly supposed to be rare. The establishment

[3] J. H. L. Vogt, *Zeitschrift für praktische Geologie*, pp. 225–238, 314–325 (July and September, 1898).

of this fact is largely due to the accuracy and completeness of the rock-analyses made by the chemists of the U. S. Geological Survey, and its great abundance was unsuspected before they began their long series of excellent analyses, though its wide distribution had been noted.

It is also noteworthy that, with the exception of iron, aluminum, manganese, and nickel, none of the metals commonly used as such appear in the list, while others, which are of very limited practical application, are present. While nearly, if not quite, all of the elements are presumably present in igneous rocks, the average amounts of those not given in the list are so extremely small that they may be regarded as minor corrections to be applied in the future to certain of those here given, since nearly all of them would be precipitated and weighed in the course of analysis with some of those more abundant.

In the important paper cited above, Vogt has discussed the probable amounts of these missing elements, and a brief statement of those of his results which pertain to the more important metallurgical elements may be given. The estimates, it must be premised, are but approximations, and only indicate the magnitude of the several amounts as percentages of the earth's crust. But they serve to show the average extremely small quantities of many metals and other elements which are usually regarded as quite common or at least not very rare.

The percentage amounts of tin, zinc, and lead are expressed by a digit in the third or fourth decimal-place, that of copper in the fourth or fifth, that of silver in the sixth or seventh, that of gold in the seventh or eighth, the amount of platinum being about the same. Mercury is rather more abundant than silver, and arsenic, antimony, molybdenum, and tungsten less than copper and greater than silver; while bismuth, selenium, and tellurium are less abundant than silver but more so than gold.

III. Petrographic Provinces.

More than 30 years ago, Vogelsang[4] pointed out that the igneous rocks of certain districts—called by him *geognostische Bezirke*—showed certain textural or mineral characters in common, which served to distinguish them from the rocks of other

[4] H. Vogelsang, *Zeitschrift der deutschen geologischen Gesellschaft*, vol. xxiv., No. 3, p. 525 (May–July, 1872).

districts. The same idea was expressed later by Judd,[5] who introduced the term Petrographic Province, and was afterward elaborated by Iddings,[6] who likened the districts of similar rocks to families and referred to their relationships as "Consanguinity." Neither Judd nor Iddings seems to have been aware of Vogelsang's prior publication. The first two statements referred only to geological occurrence and to textural and mineralogical peculiarities; while Iddings, writing at a time when the chemistry of rocks had begun to assume its due prominence (largely owing to the earnest labors of the chemists of the U. S. Geological Survey), showed that the relationship is also indicated by the chemical composition of the various rocks, and is fundamentally dependent on this, and he consequently devotes much space to the chemical evidence of consanguinity.

The doctrine of consanguinity, as it may be termed, has now received general acceptance, and it is commonly recognized that the igneous areas of the earth's surface are divisible into districts the rocks of which show certain features in common which serve to distinguish them from those of other districts. It is also assumed that the possession of these common features, especially those dependent on the chemical composition, indicates that the rocks of a given district have a common genetic origin, that is, are derived from a common parent body of magma. The processes by which this differentiation and derivation from a common magma are brought about are still obscure, and form the subject of much modern investigation and discussion, into which we cannot enter here. Such areas of related rocks are usually called petrographic provinces, though the term comagmatic region, which indicates more clearly their derivation from a common magma, has recently been introduced.[7]

Though petrographic provinces represent one of the prominent phases of the distribution of the elements in the earth's crust, and though their existence is, in general, undeniable, yet their characters are so complex and made up of so many factors that the characterization in most cases cannot be made very

[5] J. W. Judd, *Quarterly Journal of the Geological Society*, vol. xlii., pt. 1, No. 165, p. 54 (Feb. 1, 1886).

[6] J. P. Iddings, *Bulletin of the Philosophical Society of Washington*, vol. xii., pp. 128–144 (1892).

[7] H. S. Washington, *Carnegie Publication* No. 57, p. 5 (1906).

precise or the limits be very sharply drawn. Their study is still almost in its infancy, and the accumulation of many more data, especially from the analytical side, is needed before definitive studies can be undertaken, and the characters of any petrographic province be precisely defined.

The geological evidence of consanguinity is at times clear. Thus, as Iddings[8] says:

"The constant recurrence of particular series of rocks, often with a certain order of eruption in different localities, and the frequent occurrence of such series at neighboring centers of volcanic activity, would be enough to justify the belief that there was a definite connection between the members of a group."

On the other hand, cases are known where such geological evidence is lacking or conflicting, or where the relations are so generally observed as to be meaningless in this connection.

Geologically speaking, a petrographic province may belong to any period of geologic time, or may conceivably extend over more than one period. The region may be small or large, covering hundreds or hundreds of thousands of square miles. It may be of any shape, forming an elongated band or zone, a highly irregular area, or one more or less equidimensional. It may consist of a single, large area of connected intrusive or effusive rocks, or of adjacent but isolated areas.

The chemical characters which, being common to the rocks of a province, indicate consanguinity are manifold. The rocks may be uniformly high in soda or in potash, or in potash and lime, low in magnesia and high in iron, generally deficient in silica, and so on. Throughout one province the soda may increase relatively to potash as silica decreases, while in another the reverse holds good. Or again, there may be some combination of such two kinds of characters, called respectively absolute and serial. The subject is complicated by the possibility of local differentiation, so that in a region of unquestionably related rocks, we may meet with some the character of which does not conform to the general law of the region, but the presence of which is to be explained by the extreme differentiation of some portion of the general magma.

Conforming to the chemical features, and in general largely dependent on them, are the common mineralogical characters.

[8] *Loc. cit.*, p. 43

These are very important, not so much in themselves, as because they often enable one practically to determine the general relationship without the necessity of a long series of analyses. The mineralogical similarity may be evident in two ways: either by the general presence of certain minerals which are rare or are not usually found in certain kinds of rock, as the rare zirconium minerals, or nephelite, or leucite, the occurrence of hypersthene in the basalts and andesites, or of biotite in peridotites; or by certain peculiarities of color, form, or other characters shown among the more usual mineral groups, and which are dependent on the introduction of certain chemical constituents into the molecule, as bright green, pleochroic augites or blue hornblendes, due to their containing much soda, purple augites or red-brown hornblendes, due to titanium, and so on. Here again the possibilities of difference are numerous, but the mineralogical evidence of relationship is often so marked as to be unmistakable to the petrographer.

A good illustration of such petrographic provinces and of their distribution is furnished by the United States, which may be briefly described, though our knowledge is still incomplete. Stretching along and rather close to the Atlantic coast is a zone of small, isolated areas of igneous rocks which are chiefly characterized by a high content in soda, resulting in the common presence of nephelite-syenites and other rocks containing nephelite, peculiar hornblendes, and other minerals characteristic of such magmas. This zone includes areas in Quebec, New England, New Jersey, Arkansas, Texas, extends into eastern Mexico and the West Indies, and probably as far south as Brazil and Paraguay. Parallel with this, but usually farther inland, is a second zone of areas of rocks which are low in silica and the alkalies, but high in lime and iron. This starts in the great anorthosite area of eastern Canada and Labrador, appears in New England, the Adirondacks, Delaware, Maryland, and extends to Georgia and possibly farther south. The rocks of this region are typically gabbros, diabases, and pyroxenites, dunite and other peridotites, with some granites high in lime, and are often accompanied by very basic ores and other products of differentiation which are very rich in iron and titanium. Farther inland and west of the Appalachian range is another belt, less well defined but apparently in

general parallel to the others, of widely isolated small occurrences of peculiar peridotites and other rocks, low in silica and very high in magnesia and iron, with little lime or soda but much potash. This last feature gives rise to the common presence of peculiar micas, which distinguish these peridotites mineralogically from those of the preceding region. These areas occur in Quebec, New York, Pennsylvania, Kentucky, Arkansas, and probably still farther south.

Passing over the broad central part of the continent, where igneous rocks are very sparingly present, we find a province east of the Rocky mountains which is characterized by high alkalies, especially potash, so that the usually rare mineral leucite is here quite common. This region is best known in Montana, Wyoming, and Colorado, and may possibly extend into western Texas. In the region of the Rocky mountains and the cordilleras generally the occurrences of igneous rocks are so numerous and the relations so complex that it is somewhat difficult to unravel the various petrographic provinces. As a whole, however, the igneous rocks of this part of the continent seem to belong to one very extensive province, which is continued into Alaska on the north and along the Andes to the south. In general chemical character the rocks show rather low alkalies, with more soda than potash, rather high lime, and but moderate amounts of iron and magnesia, leading to the abundance of such ordinary rocks as feldspar-basalts, andesites, dacites, and some rhyolites. There is some evidence that the province as a whole may be divisible into several subordinate districts, but it is noteworthy that rocks so high in soda or potash as to contain nephelite or leucite are practically unknown west of the Rocky mountains. There are also indications of what may be a distinct region along the coast ranges which is characterized by high soda and generally high silica, but this demands further investigation.

A number of petrographic provinces outside of the United States may also be briefly indicated. One of the best known is that of southern Norway, which is prominent through the classic researches of Brögger, the rocks of which are characterized by high alkalies, especially soda, and the presence of many minerals elsewhere rare. This is possibly connected with the region of the Kola peninsula in northern Finland. The

British Islands, with the Faeroes, Iceland, and probably Spitzbergen, form another well-defined province, the rocks of which resemble on the whole those of our Rocky Mountain region, though they differ in some respects. Leaving aside Germany, Austria, and France, each of which contains several petrographic provinces, the relations of which appear to be somewhat complex, in the basin of the Mediterranean we find at least three well-defined and quite distinct provinces. In the eastern part, including the Grecian archipelago and parts of Asia Minor, the rocks are rather siliceous, with fairly high lime and rather low alkalies, soda dominating potash, so that dacites, andesites, and feldspar basalts are prominent. Hypersthene is here rather common. The Italian peninsula shows a second, very well-defined province, which embraces seven distinct volcanic centers along the west coast. The rocks of this are remarkable for their high content in potash, which at times reaches extraordinary figures, and leads to the abundant presence here of the mineral leucite, which is elsewhere decidedly rare. Lime is also rather high, while soda, iron, and magnesia are low. The other provinces of continental Italy have not been thoroughly studied and are less well known. In the western basin of the Mediterranean, including localities in Spain, Sardinia, some islands south of Sicily, and probably southern France, there appears to be a third province, which differs from the others in that soda is much higher and the more basic rocks (basalts) contain very large amounts of titanium, and in other ways. This last may be connected with a province in eastern Africa, running down the Great Rift valley and including parts of Madagascar, in which rocks rich in soda are very common. A somewhat similar province appears to exist in New South Wales and Queensland in Australia.

The descriptions just given, which are but the barest sketches of only some of those which are known, and with no references to authorities, will serve to give an idea of some of the leading distinguishing features of petrographic provinces, and how multifariously they are scattered over the earth's surface. Their existence and distribution indicate clearly that the underlying magma basins, or the sources from which the igneous rocks are immediately derived, are not everywhere uniform and alike, but that there exists a certain heterogeneity in the

non-sedimentary parts of the earth's crust. It should, however, be noted that two provinces, though widely separated, may be essentially alike in all their features, as is the case with that of the eastern Mediterranean and that which extends from the Andes to Alaska.

IV. The Correlation of the Elements.

The existence of petrographic provinces is a broad phase of the distribution of the elements among igneous rocks, the distribution being essentially a spacial one and the evidence resting almost entirely on the relative proportions of the most abundant elements. But apart from this spacial distribution there is evident, also, a correlated variation among the elements; that is, a tendency for certain ones to increase or decrease, to be relatively abundant or not, according to the presence or absence of others. The causes of this behavior are obscure and apparently complex. In part they may be probably referred to certain fundamental relations among the elements, as shown by the periodic classification and chemical affinity; in part to the effect of certain physico-chemical laws leading to the mutual segregation of elements affected similarly; and possibly in part to the degradation of some of the elements, as indicated by recent experiments of Ramsay. But any discussion of the causes is outside the province of this paper, in which we can only deal briefly with some of the facts of distribution.

The study of these mutual relations among the elements in igneous rocks is of recent date, and has been made possible, especially so far as the rarer elements go, only by the completeness and accuracy of modern chemical analyses of rocks. Such analyses supplement the evidence afforded by study of minerals, mineralogical associations, and ore-deposits, and, dealing as they do with what must be regarded as the ultimate source of the ores, are of the highest significance and importance. In the following brief discussion, therefore, stress will be laid on the evidence afforded by rock-analyses, with some reference to chemical mineralogy, while ore-deposits, as being more technical and better known to the mining engineer, will be alluded to only occasionally.

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ments and increasing completeness of modern rock-analysis show that many others are frequently present, often in scarcely more than traces, but again in very appreciable quantities. The most important of these minor elements are: zirconium, sulphur (as sulphides and as sulphur trioxide), chlorine, fluorine, vanadium, chromium, nickel, barium, strontium, and lithium. Exceptionally, others may be determined: as boron, cobalt, copper, gold, silver, molybdenum, the metals of the cerium and yttrium groups, nitrogen, and others. Indeed, as Dr. Hillebrand[1] says, "a sufficiently careful examination of these rocks would show them to contain all or nearly all the known elements, not necessarily all in a given rock, but many more than anyone has yet found." The researches of Sandberger, Stelzner, and Dieulafait also point to the same conclusion.

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TABLE I.—*Average Composition of Igneous Rocks.*

	I. United States, Clarke, 1904.	II. The World, Washington, 1903.	III. Complete Average, Clarke, 1904.		IV. Clarke, 1904.
SiO_2	60.48	57.78	59.87	O	47.09
Al_2O_3	15.17	15.67	15.02	Si	28.23
Fe_2O_3	2.61	3.31	2.58 +	Al	7.99
FeO	3.44	3.84	3.40 +	Fe	4.46
MgO	4.10	3.81	4.06	Ca	3.43
CaO	4.84	5.18	4.79	Na	2.53
Na_2O	3.43	3.88	3.39	Mg	2.46
K_2O	2.96	3.13	2.93	K	2.44
H_2O (110° +)	1.48	1.42	1.46	Ti	0.43
H_2O (110° —)	0.41	0.36	0.40	H	0.17
TiO_2	0.72	1.03	0.72	C	0.14 —
P_2O_5	0.26	0.37	0.26	P	0.11
MnO	0.10	0.22	0.10	S	0.11
CO_2	.....	.....	0.52 —	Ba	0.089
S	.....	.....	0.11	Mn	0.084
BaO	.....	.....	0.11	Cl	0.07 —
Cl	.....	.....	0.07	Sr	0.034
Cr_2O_3	.....	.....	0.05 —	Cr	0.034 —
SrO	.....	.....	0.04	Zr	0.026 —
ZrO_2	.....	.....	0.03 —	Ni	0.023 —
NiO	.....	.....	0.03 —	F	0.02 +
V_2O_3	.....	.....	0.03 —	V	0.02 —
F	.....	.....	0.02 +	Li	0.01
Li_2O	.....	.....	0.01		100.00
	100.00	100.00	100.00		

higher figure in I. may be ascribed in part, as pointed out by Clarke, to the inclusion of many separate silica-determinations, which were undertaken on rocks comparatively high in this constituent; in part to the inclusion in the estimate of some analyses of siliceous gneisses and schists, rocks which were not regarded in my estimate; and probably in part to the fact that in Clarke's estimate only rocks from the United States were considered. But notwithstanding the slight discrepancies and the uncertainty introduced by non-allowance for the disturbing factors mentioned above, the results of the two calculations are so concordant that we may feel a high degree of confidence in the belief that the data given here approximate closely to the average composition of the earth's accessible igneous rocks.

In column III. are given the results of a more complete estimate by Clarke, which includes the minor constituents frequently present in igneous rocks, but which are only deter-

mined in the more complete analyses, as those made by the chemists of the U. S. Geological Survey. It will be seen that the data are in agreement with the general composition of the most common rock-forming minerals, their constituents, silica, alumina, ferric and ferrous oxides, magnesia, lime, soda, potash, and water, making up 97.9 per cent.

The estimated amount of carbon dioxide is undoubtedly too high, and is due to the number of analyses of altered rocks which were included in the estimates.

We may examine the matter further and, resolving the oxides into their elementary components, ascertain the average amounts of the elements in the igneous crust of the earth. This problem has been studied by Clarke in the papers already cited, and by Vogt[3] in Norway. The results of Clarke's latest calculations are given in column IV. of Table I., the figures including those for the minor constituents of column III., just noticed. In an earlier computation Clarke introduced estimates of the elements which make up the air, the water of the oceans, and such non-igneous rocks as limestone and coal. But the introduction of these into the calculation does not materially alter the final results from those given here, in which they are omitted, since these bodies are of relatively very slight quantitative importance compared with the whole mass of known rocks, however large they may loom to our eyes. Ore-bodies also are quite negligible in this connection.

These data show that oxygen composes almost one-half, silicon more than one-quarter, and aluminum about one-twelfth of the earth's crust (the three together amounting to 83.3 per cent.), while iron, calcium, sodium, magnesium, potassium, and titanium follow after in the order named in decreasingly small amounts. Thus, only nine elements together constitute 99 per cent. of the igneous crust. This is certainly a very remarkable fact, and one doubtless of great significance for the proper understanding of the true constitution of our globe, could we but interpret it aright, as some day we may hope to do.

The relatively high position occupied by titanium, ninth on the list in the order of abundance, is also a striking feature, as this element is commonly supposed to be rare. The establishment

[3] J. H. L. Vogt, *Zeitschrift für praktische Geologie*, pp. 225–238, 314–325 (July and September, 1898).

of this fact is largely due to the accuracy and completeness of the rock-analyses made by the chemists of the U. S. Geological Survey, and its great abundance was unsuspected before they began their long series of excellent analyses, though its wide distribution had been noted.

It is also noteworthy that, with the exception of iron, aluminum, manganese, and nickel, none of the metals commonly used as such appear in the list, while others, which are of very limited practical application, are present. While nearly, if not quite, all of the elements are presumably present in igneous rocks, the average amounts of those not given in the list are so extremely small that they may be regarded as minor corrections to be applied in the future to certain of those here given, since nearly all of them would be precipitated and weighed in the course of analysis with some of those more abundant.

In the important paper cited above, Vogt has discussed the probable amounts of these missing elements, and a brief statement of those of his results which pertain to the more important metallurgical elements may be given. The estimates, it must be premised, are but approximations, and only indicate the magnitude of the several amounts as percentages of the earth's crust. But they serve to show the average extremely small quantities of many metals and other elements which are usually regarded as quite common or at least not very rare.

The percentage amounts of tin, zinc, and lead are expressed by a digit in the third or fourth decimal-place, that of copper in the fourth or fifth, that of silver in the sixth or seventh, that of gold in the seventh or eighth, the amount of platinum being about the same. Mercury is rather more abundant than silver, and arsenic, antimony, molybdenum, and tungsten less than copper and greater than silver; while bismuth, selenium, and tellurium are less abundant than silver but more so than gold.

III. Petrographic Provinces.

More than 30 years ago, Vogelsang[4] pointed out that the igneous rocks of certain districts—called by him *geognostische Bezirke*—showed certain textural or mineral characters in common, which served to distinguish them from the rocks of other

[4] H. Vogelsang, *Zeitschrift der deutschen geologischen Gesellschaft*, vol. xxiv., No. 3, p. 525 (May–July, 1872).

districts. The same idea was expressed later by Judd,[5] who introduced the term Petrographic Province, and was afterward elaborated by Iddings,[6] who likened the districts of similar rocks to families and referred to their relationships as "Consanguinity." Neither Judd nor Iddings seems to have been aware of Vogelsang's prior publication. The first two statements referred only to geological occurrence and to textural and mineralogical peculiarities; while Iddings, writing at a time when the chemistry of rocks had begun to assume its due prominence (largely owing to the earnest labors of the chemists of the U. S. Geological Survey), showed that the relationship is also indicated by the chemical composition of the various rocks, and is fundamentally dependent on this, and he consequently devotes much space to the chemical evidence of consanguinity.

The doctrine of consanguinity, as it may be termed, has now received general acceptance, and it is commonly recognized that the igneous areas of the earth's surface are divisible into districts the rocks of which show certain features in common which serve to distinguish them from those of other districts. It is also assumed that the possession of these common features, especially those dependent on the chemical composition, indicates that the rocks of a given district have a common genetic origin, that is, are derived from a common parent body of magma. The processes by which this differentiation and derivation from a common magma are brought about are still obscure, and form the subject of much modern investigation and discussion, into which we cannot enter here. Such areas of related rocks are usually called petrographic provinces, though the term comagmatic region, which indicates more clearly their derivation from a common magma, has recently been introduced.[7]

Though petrographic provinces represent one of the prominent phases of the distribution of the elements in the earth's crust, and though their existence is, in general, undeniable, yet their characters are so complex and made up of so many factors that the characterization in most cases cannot be made very

[5] J. W. Judd, *Quarterly Journal of the Geological Society*, vol. xlii., pt. 1, No. 165, p. 54 (Feb. 1, 1886).

[6] J. P. Iddings, *Bulletin of the Philosophical Society of Washington*, vol. xii., pp. 128–144 (1892).

[7] H. S. Washington, *Carnegie Publication* No. 57, p. 5 (1906).

precise or the limits be very sharply drawn. Their study is still almost in its infancy, and the accumulation of many more data, especially from the analytical side, is needed before definitive studies can be undertaken, and the characters of any petrographic province be precisely defined.

The geological evidence of consanguinity is at times clear. Thus, as Iddings[8] says:

"The constant recurrence of particular series of rocks, often with a certain order of eruption in different localities, and the frequent occurrence of such series at neighboring centers of volcanic activity, would be enough to justify the belief that there was a definite connection between the members of a group."

On the other hand, cases are known where such geological evidence is lacking or conflicting, or where the relations are so generally observed as to be meaningless in this connection.

Geologically speaking, a petrographic province may belong to any period of geologic time, or may conceivably extend over more than one period. The region may be small or large, covering hundreds or hundreds of thousands of square miles. It may be of any shape, forming an elongated band or zone, a highly irregular area, or one more or less equidimensional. It may consist of a single, large area of connected intrusive or effusive rocks, or of adjacent but isolated areas.

The chemical characters which, being common to the rocks of a province, indicate consanguinity are manifold. The rocks may be uniformly high in soda or in potash, or in potash and lime, low in magnesia and high in iron, generally deficient in silica, and so on. Throughout one province the soda may increase relatively to potash as silica decreases, while in another the reverse holds good. Or again, there may be some combination of such two kinds of characters, called respectively absolute and serial. The subject is complicated by the possibility of local differentiation, so that in a region of unquestionably related rocks, we may meet with some the character of which does not conform to the general law of the region, but the presence of which is to be explained by the extreme differentiation of some portion of the general magma.

Conforming to the chemical features, and in general largely dependent on them, are the common mineralogical characters.

[8] *Loc. cit.*, p. 43

These are very important, not so much in themselves, as because they often enable one practically to determine the general relationship without the necessity of a long series of analyses. The mineralogical similarity may be evident in two ways: either by the general presence of certain minerals which are rare or are not usually found in certain kinds of rock, as the rare zirconium minerals, or nephelite, or leucite, the occurrence of hypersthene in the basalts and andesites, or of biotite in peridotites; or by certain peculiarities of color, form, or other characters shown among the more usual mineral groups, and which are dependent on the introduction of certain chemical constituents into the molecule, as bright green, pleochroic augites or blue hornblendes, due to their containing much soda, purple augites or red-brown hornblendes, due to titanium, and so on. Here again the possibilities of difference are numerous, but the mineralogical evidence of relationship is often so marked as to be unmistakable to the petrographer.

A good illustration of such petrographic provinces and of their distribution is furnished by the United States, which may be briefly described, though our knowledge is still incomplete. Stretching along and rather close to the Atlantic coast is a zone of small, isolated areas of igneous rocks which are chiefly characterized by a high content in soda, resulting in the common presence of nephelite-syenites and other rocks containing nephelite, peculiar hornblendes, and other minerals characteristic of such magmas. This zone includes areas in Quebec, New England, New Jersey, Arkansas, Texas, extends into eastern Mexico and the West Indies, and probably as far south as Brazil and Paraguay. Parallel with this, but usually farther inland, is a second zone of areas of rocks which are low in silica and the alkalies, but high in lime and iron. This starts in the great anorthosite area of eastern Canada and Labrador, appears in New England, the Adirondacks, Delaware, Maryland, and extends to Georgia and possibly farther south. The rocks of this region are typically gabbros, diabases, and pyroxenites, dunite and other peridotites, with some granites high in lime, and are often accompanied by very basic ores and other products of differentiation which are very rich in iron and titanium. Farther inland and west of the Appalachian range is another belt, less well defined but apparently in

general parallel to the others, of widely isolated small occurrences of peculiar peridotites and other rocks, low in silica and very high in magnesia and iron, with little lime or soda but much potash. This last feature gives rise to the common presence of peculiar micas, which distinguish these peridotites mineralogically from those of the preceding region. These areas occur in Quebec, New York, Pennsylvania, Kentucky, Arkansas, and probably still farther south.

Passing over the broad central part of the continent, where igneous rocks are very sparingly present, we find a province east of the Rocky mountains which is characterized by high alkalies, especially potash, so that the usually rare mineral leucite is here quite common. This region is best known in Montana, Wyoming, and Colorado, and may possibly extend into western Texas. In the region of the Rocky mountains and the cordilleras generally the occurrences of igneous rocks are so numerous and the relations so complex that it is somewhat difficult to unravel the various petrographic provinces. As a whole, however, the igneous rocks of this part of the continent seem to belong to one very extensive province, which is continued into Alaska on the north and along the Andes to the south. In general chemical character the rocks show rather low alkalies, with more soda than potash, rather high lime, and but moderate amounts of iron and magnesia, leading to the abundance of such ordinary rocks as feldspar-basalts, andesites, dacites, and some rhyolites. There is some evidence that the province as a whole may be divisible into several subordinate districts, but it is noteworthy that rocks so high in soda or potash as to contain nephelite or leucite are practically unknown west of the Rocky mountains. There are also indications of what may be a distinct region along the coast ranges which is characterized by high soda and generally high silica, but this demands further investigation.

A number of petrographic provinces outside of the United States may also be briefly indicated. One of the best known is that of southern Norway, which is prominent through the classic researches of Brögger, the rocks of which are characterized by high alkalies, especially soda, and the presence of many minerals elsewhere rare. This is possibly connected with the region of the Kola peninsula in northern Finland. The

British Islands, with the Faeroes, Iceland, and probably Spitzbergen, form another well-defined province, the rocks of which resemble on the whole those of our Rocky Mountain region, though they differ in some respects. Leaving aside Germany, Austria, and France, each of which contains several petrographic provinces, the relations of which appear to be somewhat complex, in the basin of the Mediterranean we find at least three well-defined and quite distinct provinces. In the eastern part, including the Grecian archipelago and parts of Asia Minor, the rocks are rather siliceous, with fairly high lime and rather low alkalies, soda dominating potash, so that dacites, andesites, and feldspar basalts are prominent. Hypersthene is here rather common. The Italian peninsula shows a second, very well-defined province, which embraces seven distinct volcanic centers along the west coast. The rocks of this are remarkable for their high content in potash, which at times reaches extraordinary figures, and leads to the abundant presence here of the mineral leucite, which is elsewhere decidedly rare. Lime is also rather high, while soda, iron, and magnesia are low. The other provinces of continental Italy have not been thoroughly studied and are less well known. In the western basin of the Mediterranean, including localities in Spain, Sardinia, some islands south of Sicily, and probably southern France, there appears to be a third province, which differs from the others in that soda is much higher and the more basic rocks (basalts) contain very large amounts of titanium, and in other ways. This last may be connected with a province in eastern Africa, running down the Great Rift valley and including parts of Madagascar, in which rocks rich in soda are very common. A somewhat similar province appears to exist in New South Wales and Queensland in Australia.

The descriptions just given, which are but the barest sketches of only some of those which are known, and with no references to authorities, will serve to give an idea of some of the leading distinguishing features of petrographic provinces, and how multifariously they are scattered over the earth's surface. Their existence and distribution indicate clearly that the underlying magma basins, or the sources from which the igneous rocks are immediately derived, are not everywhere uniform and alike, but that there exists a certain heterogeneity in the

non-sedimentary parts of the earth's crust. It should, however, be noted that two provinces, though widely separated, may be essentially alike in all their features, as is the case with that of the eastern Mediterranean and that which extends from the Andes to Alaska.

IV. The Correlation of the Elements.

The existence of petrographic provinces is a broad phase of the distribution of the elements among igneous rocks, the distribution being essentially a spacial one and the evidence resting almost entirely on the relative proportions of the most abundant elements. But apart from this spacial distribution there is evident, also, a correlated variation among the elements; that is, a tendency for certain ones to increase or decrease, to be relatively abundant or not, according to the presence or absence of others. The causes of this behavior are obscure and apparently complex. In part they may be probably referred to certain fundamental relations among the elements, as shown by the periodic classification and chemical affinity; in part to the effect of certain physico-chemical laws leading to the mutual segregation of elements affected similarly; and possibly in part to the degradation of some of the elements, as indicated by recent experiments of Ramsay. But any discussion of the causes is outside the province of this paper, in which we can only deal briefly with some of the facts of distribution.

The study of these mutual relations among the elements in igneous rocks is of recent date, and has been made possible, especially so far as the rarer elements go, only by the completeness and accuracy of modern chemical analyses of rocks. Such analyses supplement the evidence afforded by study of minerals, mineralogical associations, and ore-deposits, and, dealing as they do with what must be regarded as the ultimate source of the ores, are of the highest significance and importance. In the following brief discussion, therefore, stress will be laid on the evidence afforded by rock-analyses, with some reference to chemical mineralogy, while ore-deposits, as being more technical and better known to the mining engineer, will be alluded to only occasionally.

Considering first only the most abundant elements, a study

of the igneous rocks in general shows that silica, alumina, soda, and potash tend to increase or decrease together, though not always at the same rate; while, on the other hand, the iron oxides, magnesia, and lime tend to vary together and in general inversely as the preceding constituents. The more siliceous rocks almost invariably show relatively high alumina and alkalies and low iron oxides, magnesia, and lime, leading to the common presence in abundance of the alkali feldspars and the comparative paucity in calcic feldspars and the ferromagnesian minerals, which tend to increase rapidly with diminution in the silica-content. Highly siliceous rocks which contain more iron, magnesia, and lime than alumina, soda, and potash are of very exceptional occurrence. The rule mentioned above is so generally true that it may be regarded as the normal one for igneous rocks in general, and is commonly accepted as such in petrology.

At the same time, there is considerable evidence that certain subsidiary relations obtain among the constituents other than silica, which, while by no means universal, are at times very pronounced, and occasionally seem to supersede the more general law. Thus, soda not uncommonly tends to vary with the iron oxides, while potash shows similar relations to magnesia, resulting in the presence of potassium minerals in highly magnesian rocks and the abundance of sodium minerals in those high in iron. Again, while neither iron nor magnesia shows any marked affinity towards or tendency to vary with alumina, this constituent and lime are occasionally found to occur together in great abundance and to the general exclusion of the others. These relations are also evident in certain facts of chemical mineralogy, as the usual predominance of magnesium over iron in the potassic biotites and phlogopites, the abundance of soda and absence of potash among the highly ferriferous augites and hornblendes, and the numerous silico-aluminates containing much calcium, while those with iron or magnesium are comparatively very rare.

But this tendency to selective and correlated variation among the chemical constituents of igneous rocks is not confined to those which are present in greatest amount. It is equally well, and indeed in some respects more strikingly, shown among the rarer elements, both as compared with those which are most

abundant and with each other. Furthermore, the distribution of some of these rare elements would seem to have important bearings on some of the problems of economic geology and the distribution of ore-deposits.

The general facts of this distribution and variation of the rare elements have been summarized in several recent publications,[9] but many of the details are still un-coördinated and widely scattered through the vast mass of petrographic literature, and there are certain aspects and recent developments which are either neglected, or only briefly alluded to, in the publications cited.

It is now commonly understood that certain elements are prone to occur most often and in largest amounts in rocks which are high in silica, the so-called "acid" rocks; while others are met with similarly in those low in silica—the "basic" rocks. This is essentially the only set of relations recognized by Vogt, while De Launay in addition to these two groups proposes two others, the "mineralizing agents" and the vein-metals.

Evidence, however, is accumulating that the relations of the rare elements to the igneous rocks cannot be expressed so simply as is done by Vogt and De Launay. Their relative abundance is not dependent on the silica alone, and hence referable only to the "acidity" or "basicity" of the rock. The relations are more complex, and dependent, not so much on the amount of silica, as on the relative amounts of other constituents, notably soda, potash, iron, magnesia, or lime. They conform, on the whole, to the general relations of the most abundant constituents, some of the rarer elements being characteristically at home in the rock groups which show high alumina and alkalies, and which include those high in silica; while others again are most abundant in the rocks high in iron, magnesia, or lime, and which consequently most often show low silica percentages. Further than this, on the one hand, certain rare elements are not equally at home in the alkalic

[9] J. H. L. Vogt, *Zeitschrift für praktische Geologie*, p. 326 (September, 1898); J. F. Kemp, *Ore Deposits*, 3d edition, pp. 34–37 (1900); H. S. Washington, *Manual of the Chemical Analysis of Rocks*, p. 14 (1904); L. De Launay, *La Science Géologique*, p. 637 (1905); W. F. Hillebrand, *Bulletin No.* 305, *U. S. Geological Survey*, p. 21 (1907).

rocks in general, but are most abundant either in those high in soda or in those high in potash. On the other hand, some of the elements segregated in the basic rocks seem to be most at home in those which are highly calcic, others in those which are high in iron or in magnesia, though here the evidence is not so clear and the distinctions apparently not so well marked as in the preceding case.

We may consider first those minor constituents of rocks which are determined in the most modern and complete analyses, and next those which exist in rocks in such small amount as almost to defy determination by the usual analytical methods, but whose presence is made known either mineralogically or by their segregation in ore-deposits. The second group includes almost all of the commercially important metals (except iron and manganese), while the former includes many elements which are assuming an increased practical importance as their economic possibilities and uses become better known. In a general way the elements will be taken up in the order of their positions in the periodic classification. No references will be given, as an attempt to render them complete would unduly lengthen the paper. This course seems the more advisable, in spite of the apparent injustice to those whose invaluable work and contributions must thus be ignored, since the present paper may be considered as merely a preliminary one to a more exhaustive and monographic treatment which it is hoped to publish later.

Lithium is very widely distributed among igneous rocks, but always in very small amounts. While it frequently is to be detected by the spectroscope, it seldom occurs in weighable quantities, and the difficulty of its exact separation from the other alkali metals and its comparative unimportance cause it to be but seldom estimated quantitatively. Although such minute traces are present in both acid and basic rocks, yet it is undoubtedly more closely connected with those which are highly siliceous and alkalic. The minerals in which it forms an essential component, as spodumene, lepidolite, amblygonite, and some tourmalines, are most often met with in granites and pegmatites derived from granitic magmas. Unfortunately, the granites and pegmatites which carry lithium minerals most prominently do not appear to have been analyzed,

but there is reason for the belief that they are sodic rather than potassic in general character. The very common association of lithium with soda rather than with potash in many minerals also points to the same conclusion.

Beryllium is much like lithium in its associations, beryl and other rarer minerals which contain it occurring for the most part in granites or pegmatites. Few analyses exist of such beryl-bearing rocks, and beryllia has seldom been estimated separately from alumina in rock-analysis, but such data as are available and the common mineralogical association of beryllium and sodium point to the conclusion that the element is most at home in sodic magmas.

Attention may be called to the fact that beryl, in spite of its common occurrence, is not given in the list of descriptions of the rock-forming minerals, such as those in the standard works of Zirkel, Rosenbusch, and Iddings, though Lévy and Lacroix briefly described it in their work[10] and it is placed on their large colored table of bi-refringences. In its optical properties it closely resembles nephelite and apatite, and being hexagonal in crystallization as well, might readily be mistaken for one of these minerals. I have noted the fact that analyses of nephelite-syenites and other highly sodic rocks frequently show a decided excess of alumina which cannot be explained by the apparent mineralogical composition of the rock, and the suggestion is made that this is possibly due to the presence of beryl, the beryllia of which would appear as alumina in the course of analysis, unless special means were taken to separate the two. On the other hand, the excess of alumina may be real and due to the composition of the magma.

Strontium has been shown by the analyses of the U. S. Geological Survey to be widely distributed in the rocks of this country. I have found it almost invariably when looked for in many European rocks, and it is almost constantly present in those of Australia. But it seldom occurs in more than traces, and the evidence in regard to its distribution is as yet inconclusive, in spite of the many modern analyses in which it is now determined, chiefly because of the small amounts usually met with. It would appear to be most abundant in rocks somewhat high in lime and with moderate to rather low silica,

[10] *Les Minéraux des Roches* (Paris, 1888).

though it is worthy of note that the highest figures recorded for it are in some rocks of Wyoming which are low in lime and extraordinarily high in potassium and barium. Being but rarely a constituent of silicate minerals, decisive evidence from this side is wanting, though it occurs with lime in some heulandite and brewsterite.

Barium is another element which the analyses of the Washington chemists showed to be widely distributed, and almost invariably in decidedly greater amounts than strontium. It is now often determined by analyses of superior quality, and in a recent study, embracing the rocks of Italy, the United States, and New South Wales, I have shown that it is specially prone to occur in potassic rocks, sometimes when the potash is accompanied by considerable lime, but that it is rarely met with in notable amount in decidedly sodic or calcic rocks. Neither the amount of silica nor the relative proportions of iron and magnesia, appears to be a determining factor of much importance. This association of barium and potassium in igneous rocks is in harmony with the mineralogical evidence. Barium is a frequent minor constituent in potassium minerals, as orthoclase, muscovite, and biotite, while potassium accompanies barium in hyalophane and harmotome. On the other hand, barium is not reported in analyses of sodium minerals, but occurs in small amounts in the calcium zeolites, brewsterite and phillipsite. Barium also seems to tend to associate with manganese, as shown by its common occurrence in psilomelane, and the occurrence of minerals of the two metals in certain mines.

Boron is seldom or never mentioned in rock-analyses, chiefly because of the complexity and difficulty of its exact determination, especially in very small amounts. But it is not infrequently present in weighable amounts in granites and pegmatites, chiefly as a constituent of tourmaline. The few analytical data that we have of such tourmaline-bearing rocks are not decisive, but boron does not appear to have very decided preferences for either soda or potash. Its associations in minerals are likewise not strongly marked, but among the silicates calcium is the basic element which most frequently accompanies it, and soda is more commonly met with in boron-bearing minerals than is potash. Boron is commonly regarded as one of the pneumatolytic elements.

Cerium, *yttrium*, and the other metals of the so-called "rare earths," as well as *thorium* and *uranium*, are only rarely determined in rock-analysis. Minerals containing them are commonly associated with acid pegmatites, which, judging from occurrences in Norway, Greenland, and elsewhere, are most apt to be sodic, though the few determinations available of the rare earths are in highly potassic igneous rocks.

Titanium is, as we have seen, far from being the rare element which it was formerly considered, and it is probably never wholly absent from any rock. It is distinctly much more abundant in basic than in acid rocks, and its affinities in the magma seem to be decidedly rather with iron than with magnesium, and still less with lime. While it is not commonly associated with alkalic rocks, yet when these are low in silica it shows a tendency to be present in considerable amount when the rock is sodic, as indicated by recent rock-analyses; and this tendency to association of titanium with sodium appears mineralogically, as in the soda-amphiboles, some of which are highly titaniferous, and in certain rare minerals, as astrophyllite and rosenbuschite. Highly potassic and highly calcic rocks seldom show large amounts of titanium, though most of the mineral titanates contain calcium as the base.

Zirconium, so closely allied to titanium chemically, also shows certain analogies in its magmatic relations. While unlike titanium in being rare in the basic rocks, those high in iron, magnesia, and lime, and referred by Vogt to the acid rocks, presumably because of the common occurrence of zircons in granites, it is now commonly recognized by petrographers that zirconium is by far most abundant in the rocks which are high in soda. Indeed, zirconium may be considered to be a characteristic minor chemical constituent of the sodic rocks, whether the silica be so high that quartz is present, or whether it be so low that nephelite is abundant, as in the nephelite-syenites and phonolites. Practically all modern, complete analyses bear out this view, which is confirmed by the common association of sodium and zirconium mineralogically, as in eudialyte, catapleiite, wöhlerite, and the zirconium pyroxenes.

Phosphorus, as a constituent of apatite, is universally diffused in small amounts through igneous rocks, and is most abundant in the basic ones, though its relations to the constituents

other than silica are not clear. Study of large collections of analyses indicates that it is usually, but not always, associated with high lime, rather than with high iron or magnesia, and in some distinctly sodic provinces the more basic rocks with high soda and abundant nephelite show high figures for phosphorus pentoxide. Some of the phosphates are met with in granitic and syenitic pegmatites.

Vanadium has been shown by the researches of Hillebrand to be quite widely distributed, but always in very small amount and almost wholly confined to the basic rocks. As it exists as the sesquioxide, V_2O_3, replacing alumina and ferric oxide in ferro-magnesian minerals, it is especially abundant in rocks composed largely of pyroxene, hornblende, or biotite, while it is present only in traces or not at all in rocks very rich in olivine, where the iron is present mostly as ferrous oxide, as in the peridotites. It is associated with iron rather than with magnesium, and occurs in most abundance in some iron-ores of magmatic origin, but no definite relations to the alkalies can be made out. Its common occurrence in ashes of coals and its abundance in certain carbonaceous deposits recently described are noteworthy, though outside the present discussion.

Sulphur is, by far, more abundant in the basic than in the siliceous rocks. It may exist, in the oxidized condition, in the minerals hauynite and noselite, in which case the rocks containing these minerals are almost invariably distinctly sodic; or it may form sulphides, as pyrite, pyrrhotite, and chalcopyrite, these being most common in rocks rather high in iron, magnesia, and lime.

Chromium, like vanadium, is a constituent of the basic rocks, but, unlike this, is most abundant when magnesia and not iron is high, and when olivine, rather than pyroxene or hornblende, is abundant, in spite of the fact that it occurs as the sesquioxide, Cr_2O_3. Presumably this is because, instead of replacing alumina and ferric oxide in the ferromagnesian minerals, it is most commonly met with in the minerals chromite and picotite. It is reported to reach very high figures again in certain effusive rocks which are so high in lime and low in silica that the rare mineral melilite is present.

Molybdenum is seldom looked for in rock-analysis, and our knowledge of its magmatic relations is based almost wholly on

an investigation by Hillebrand. He found that it is much less common and is present in smaller quantity than vanadium, and that, unlike the latter, it is present only in the more siliceous rocks, though in quantities too small to permit of further discrimination. As molybdenite it occurs most often in quartzose rocks.

Fluorine is almost universally present in very small amount as a constituent of most apatites, and is usually regarded as a "mineralizing agent," and, as such, is frequently present in pneumatolytic minerals. As stated by Vogt, it seems to be more common in the acid rocks, but there seems to be a marked tendency on its part to favor especially rocks which are high in soda. This is seen in the fact that fluorite is frequently present as an original constituent of such highly sodic rocks as nephelite-syenite, phonolite, and tinguaite; the association of fluorine and sodium in certain rare minerals, as leucophanite, meliphanite, johnstrupite, rinkite, etc., which are almost always found in sodic rocks; and by the recent discovery by Lacroix of sodium fluoride in nephelite-syenites of West Africa.

Chlorine resembles fluorine in being a pneumatolytic constituent, and is present in igneous rocks chiefly in the minerals sodalite and noselite, which are almost wholly confined to sodic rocks and especially those which are low in silica, in this resembling the occurrence of SO_3.

Manganese, though as widely distributed as titanium and phosphorus, is usually present in such small amounts as not to allow a clear judgment of its magmatic relations, especially as the high figures often reported for it are apt to be due to analytical error. As a general rule, its amount is greater in the basic rocks, and certain considerations indicate a preference for rocks high in iron rather than in magnesia or lime, but the variations are not very significant. We have already noted above the tendency to association of barium and manganese.

Nickel is pre-eminently at home in the basic rocks, especially in the peridotites and serpentines, where it replaces iron in the olivine, while it likewise occurs in small amounts in hornblende, biotite, and in pyrite and pyrrhotite. Certain rather high figures reported for it may be ascribed to analytical confusion with platinum derived from the utensils employed; but

researches now in progress indicate that it may be present in considerable amount (up to about 0.20 per cent.), not only in the "basic" but in the more siliceous rocks of certain localities where its presence has not hitherto been suspected. It is reasonable to suppose that it is most apt to be present in rocks which are relatively high in iron rather than in magnesia and lime, and the results of the investigation just mentioned are in harmony with this supposition.

Cobalt almost always accompanies nickel in igneous rocks, but always in extremely small and scarcely weighable amounts.

The elements belonging to the next group to be discussed, those which are scarcely detectable in igneous rocks by the usual analytical methods on account of the excessively minute amounts usually present, need not detain us long, even though they are commercially among the most important. Since the analytical data are either very scanty, untrustworthy, or wanting altogether, and their presence is revealed to us mostly through secondary processes of concentration in veins, placers, and other ore-deposits, we are not yet in a position to generalize with confidence as to the magmatic relations of most of them.

Furthermore, having but slight affinity for silica, and thus (with few exceptions) seldom forming silicates or entering as minor constituents into the silicate minerals of other elements, we are deprived to a very great extent of this kind of evidence.

Copper is not infrequently reported in analyses of igneous rocks, but, as pointed out by Hillebrand, its apparent presence may often be attributed to contamination during the course of analysis, or, as may be suggested here, to confusion with platinum likewise due to contamination, as was suggested in the case of nickel. But notwithstanding these sources of error copper seems to be widely distributed among igneous rocks, though in very small amounts. There seems to be little doubt that it is most abundant in the more basic rocks, especially those which carry pyroxene and hornblende rather than olivine, but no evidence seems to exist as to its relations to the chemical constituents other than silica.

Silver and *gold* have both been detected analytically in igneous rocks, while metallic gold has also been observed as an apparently primary ingredient of some rhyolites and granites. Both of these metals are "cosmopolitan in their relations," as

Kemp puts it, and they are known to occur in such highly siliceous rocks as granite, rhyolite, and quartz-porphyry, and, on the other hand, in diabase and gabbro. There is, however, good reason for the belief that gold, and probably silver as well, are most apt to occur in rocks high in silica, but their relations to the other elements are still quite unknown.

Zinc and *cadmium* (which latter is found only in connection with the former) are also very uncertain. There is, however, some reason for thinking that zinc is more apt to be present in acid rocks, as granites, this opinion being based on a few analytical data and the facts of some of its occurrences. The common occurrence of zinc in limestones, due presumably, at least in part, to the precipitating effect of the sedimentary rock, has no apparent bearing on its relations to igneous magmas.

Mercury is considered by G. F. Becker to be associated with granites, but his evidence is not very convincing. Its usual occurrence in sedimentary rocks tends to obscure its true relations, and, to the best of my knowledge, it has never been looked for or reported in an analysis of an igneous rock.

Tin, as the oxide, cassiterite, almost invariably occurs as the result of pneumatolytic processes in pegmatites, granites, and other rocks high in silica, and the mineral has been found in some rhyolites. Judging from the common association of cassiterite with lithium and beryllium minerals, and the presence of small amounts of tin in certain feldspars, micas, zircons, and in the rare mineral stokesite, it is probable that tin is associated rather with distinctly sodic than with potassic or calcic magmas, but much more chemical study of the rocks in which it occurs is needed to elucidate its relations.

Lead can often be found in rocks by using large amounts of material, and is occasionally reported, as in the analyses of rocks from British Guiana by J. B. Harrison and in those of rocks from New South Wales. No generalization in regard to it is possible as yet, but I am inclined to think that, like zinc, it favors the acid rather than the basic rocks, though it has been observed in both. The remarks in regard to the occurrence of zinc in limestones apply as well to lead.

Platinum and the other metals of this group are, as is well known, most commonly found in connection with peridotites, rocks low in silica and high in magnesia, though it has been

observed by Kemp in gabbros, which were presumably connected genetically with peridotitic rocks. Recent developments point to a somewhat wider distribution than was formerly thought to be the case, and indicate that platinum not infrequently is associated with copper-ores.

The true relations of such elements as *arsenic*, *antimony*, *bismuth*, *selenium* and *tellurium* to igneous magmas are quite unknown. It is possible that arsenic and selenium are most at home in the basic rocks, while antimony, bismuth, and tellurium are more apt to occur in siliceous ones.

We may summarize the observations recorded above as follows: Of the rarer elements whose distribution is better known, lithium, beryllium, cerium and yttrium, zirconium, uranium, thorium, sulphur (as trioxide), fluorine, chlorine, and possibly tin occur most abundantly in sodic magmas; barium in potassic magmas; titanium, vanadium, manganese, nickel, and cobalt in iron-rich magmas; chromium and platinum in magnesian magmas; and phosphorus (?) and chromium (?) in calcic magmas.

Of the other elements it can only be said that boron and molybdenum are certainly, and zinc, cadmium, lead, antimony, bismuth, and tellurium are possibly, connected with magmas high in silica; sulphur and copper almost certainly, and arsenic and selenium possibly, with those low in silica; while the relations of gold, silver, and mercury are very uncertain, but they are probably most at home in acid rocks.

This statement, it will be seen, differs from that of Vogt, in that, in the best-established cases, silica plays a less determinative rôle than some of the other major constituents. At the same time, the influence of the general law of the association of the most abundant oxides comes into play, and in a general way the potassic and sodic magmas are most apt to be highly siliceous (though the facts of distribution are shown in them even when silica is low); while those which are high in iron, magnesia, and lime are most apt to be low in silica.

Possibly the most striking feature of the distribution as thus shown is the great number of elements which are prone to occur in highly sodic magmas. As is well known, such magmas are those which show most tendency to differentiation and the formation of a great variety of rocks, many of them character-

ized by the presence of rare or otherwise unusual and interesting minerals, and there may probably be some connection between the two features of these magmas.

It will be noted that some of these elements, as fluorine, chlorine, sulphur (as trioxide), and boron, are among those to which is usually attributed the rôle of so-called "mineralizing agents," they being supposed to be present as dissolved vapors in the magma and to exert a marked effect on the crystallization of the mass, the formation of pegmatites, and so forth. It may be argued that such mineralizing and pneumatolytic elements are universally, and presumably quite uniformly, distributed among the rock-magmas, and that their presence in the highly siliceous and sodic rocks is due to the greater viscosity of these when molten, which would hinder the escape of gaseous constituents, while the basic magmas are more fluid at low temperatures and would hence allow such gases to escape before or during consolidation. On the other hand, it may be urged that the undeniable distribution, among magmas of distinctly different general chemical characters, of elements to which no such mineralizing or pneumatolytic rôle can be reasonably assigned, as barium, beryllium, zirconium, titanium, manganese, nickel, chromium, and platinum, would lead to the inference that the apparent distribution of the gaseous and "mineralizing" elements in igneous rocks is real and not dependent on physical causes. The subject is highly complex, and our knowledge of the fundamental facts and of the physico-chemical laws involved is as yet inadequate for solution of the problem, further discussion of which would be outside the scope of this paper.

V. Practical Considerations.

When the facts of the relations of the occurrence of the rarer elements to the chemical characters of igneous magmas are considered, it is evident that their distribution over the earth's surface must be largely determined by that of the petrographic provinces. In other words, in any given petrographic province those rarer elements and minerals containing them would be most apt to occur abundantly which show a correlative tendency to association with the characteristic major constituents of the province. Thus, zirconium-bearing minerals and those of the "rare earths" should be most abundant in

provinces whose magmas are highly sodic and where such rocks as nephelite-syenite and phonolite are common; while chromium, nickel, and platinum would not be expected in these, but would rather be likely to occur in provinces where such rocks as gabbros and peridotites are the prevailing ones.

This idea has been recognized by Spurr[11] in his proposed term of "metallographic provinces," which is based largely on ore-associations, and which he applies more especially to those metals of most economic importance, such as gold, silver, copper, lead, and zinc. The probable very close connection between "petrographic" and "metallographic" provinces is pointed out by him, but the two classes seem to be regarded by him as distinct, at least to a certain extent.

When we deal with such complex bodies as veins and other ore-deposits, the matter is complicated by such factors as geological structure, the existence of faults, the occurrence of the igneous rock as plutonic masses, dikes or effusive flows, climatic conditions,[12] and other disturbing features. These may tend either to favor or to retard the processes of concentration which result in economically-exploitable metalliferous deposits. But these, though undoubtedly of the highest commercial importance, are subsidiary to the more fundamental facts of the distribution of the elements in igneous magmas, and it seems reasonable to suppose that a study of these latter features should be susceptible of results of great practical importance.

It seems that, at present, the knowledge gained by exact chemical analysis that the granites of a certain region contain minute traces of gold or of copper, would be of little use in guiding one in the search for the location of a gold- or a copper-mine. The prospector must always remain a valuable, indeed an invaluable, member of the mining fraternity. We cannot enter here into the vast and vexed subject of the genesis of ore-deposits, but if it were known by future researches that, for instance, gold or copper is normally associated with magmas of a certain general chemical character, a knowledge of this might conceivably be of material assistance in a search; not so much by

[11] *Trans.*, xxxiii., 336 (1902); *Professional Paper* No. 42, *U. S. Geological Survey*, p. 276 (1905); and No. 55, p. 128 (1906).

[12] H. V. Winchell, *Popular Science Monthly*, vol. lxxii., No. 6, pp. 534 to 542 (June, 1908).

indicating the exact position of a favorable location, but, in a more general way, by leading the prospector to confine his attention to a given region of favorable igneous rocks, and to disregard one whose rocks, on theoretical grounds, would probably result in loss of time and effort. Such a knowledge could be gained, not only by the complex and laborious methods of accurate and minutely complete chemical analysis, but more readily, at least in many conceivable cases, by simple petrographical examination and field-study of the most abundant and characteristic rock-minerals.

These considerations, it is true, are scarcely applicable as yet to search for such metals as gold, silver, or copper, concerning the magmatic relations of which our knowledge is of the vaguest description. But, in view of what has been ascertained by petrographical and chemical means of the distribution of other elements, it is not unreasonable to think that we shall eventually obtain well-founded and definite knowledge concerning the distribution of these also. Indeed, the opinion may be expressed that future petrographers will wonder at the fact that, for instance, the presence of such deep-seated and extensive deposits of copper as those at Butte, Mont., and in Shasta county, Cal., was so long unsuspected, and that their discovery came as a surprise.

At the present time a knowledge of the distribution of the elements is practically applicable, not so much to the metals of greatest human utility, as to certain elements the economic possibilities of which are only recently beginning to be appreciated as their chemical and physical properties and the application of these to commercial and economic purposes are becoming better known. Some illustrations may be permitted of the practical application of the facts set forth in the preceding pages.

If, for instance, one were in a new country or were engaged in a search for minerals containing such elements as zirconium, uranium, the rare earths, or beryllium, one would welcome a district of highly sodic igneous rocks, where albitic granites, nephelite-syenites, and phonolites were abundant; in this the chances of success would be most favorable. If the rocks were prevailingly gabbros, diabases, or feldspar-basalts one would reasonably assume that such minerals could not be expected to

occur, at least in such amount as to repay exploitation, and they would be neglected, or prospected for platinum or chromium, let us say. Similarly, if the platinum metals were found in the sands of a river the water-shed of which covered areas of gabbros, granites, and limestones, one would naturally turn to and explore the first in an attempt to trace the grains to their source, and would, with good reason, leave the others alone.

Instances of this kind could be multiplied, and, indeed, some present applications of the general principles are now practiced not infrequently, but without any suspicion of the true principles underlying them or realization of their more general applicability. Thus, in certain districts the occurrence of topaz or spodumene may be recognized as generally indicating the possible or probable presence of cassiterite, without appreciation of the more general and fundamental fact that the conjunction of tin, fluorine, and lithium is due to the distinctly sodic character of the igneous rocks.

With increase in our knowledge of the origin of ore-deposits, and a general agreement as to their ultimate source in igneous rocks (whatever be the divergence of views as to the processes of concentration), the probability of the future importance of such observations as have been outlined above, from a practical as well as from a theoretical standpoint, is fairly evident. We cannot as yet predict the probable presence of gold, silver, or copper in economic quantities from the petrographical and chemical study of the country-rock; but the time may come (and our increasing knowledge of igneous rocks justifies us in a certain degree of confidence that it will come) when such seemingly erudite and impractical studies will be able to guide us in certain regions, as to either the probable absence or presence of ore-bodies of such metals.

The problem is admittedly very complex, and is one which has not yet been studied enough to do much more than enable us to make a few broad guesses at the truth. But we are beginning to discern some glimmer of light, and the fact that we cannot make out clearly our guiding stars, veiled as they are by the mists of imperfect knowledge, should not cause us to disdain such help as glimpses of them may now afford, or underrate their possible importance when the mists shall have been dispelled.

No. 29.

The Agency of Manganese in the Superficial Alteration and Secondary Enrichment of Gold-Deposits in the United States.*

BY WILLIAM H. EMMONS, CHICAGO, ILL.

(Canal Zone Meeting, November, 1910. *Trans.*, xlii., 3.)

CONTENTS.

PAGE.

I. INTRODUCTION AND SUMMARY, ... 760

II. SALTS CONTAINED IN THE WATERS OF GOLD- AND SILVER-MINES IN NON-CALCAREOUS ROCKS, ... 764

1, Sulphates; 2, Chlorides; 3, Carbonates and Alkaline Earths; 4, Alumina; 5, Nitrates; 6, Phosphates; 7, Silica; 8, Iron; 9, Manganese; 10, Copper.

III. CHEMICAL EXPERIMENTS IN THE SOLUTION AND DEPOSITION OF GOLD, 771

IV. DISCUSSION OF EXPERIMENTS, ... 776

1, Nitrates; 2, Manganese Oxides; 3, Lead Oxides; 4, Ferric Compounds; 5, Efficiency of Ferric Iron and of Cupric Copper to Supply Nascent Chlorine, Compared with that of Manganitic Manganese; 6, The Amount of Chlorine Necessary for the Solution of Gold in the Presence of Manganese Compounds; 7, The Precipitation of Gold.

V. THE TRANSFER OF GOLD IN COLD SOLUTIONS, ... 785

1, Restatement of the Processes as Related to Secondary Enrichment; 2, Association of Gold with Manganese Oxides; 3, The Oscillating, Descending, Undulatory Water-Table; 4, The Several Successive Zones in Depth; 5, Criteria for the Recognition of Secondary Enrichment; 6, Lateral Migration of Manganese-Salts from the Country-Rock to the Ore; 7, Concentration in the Oxidized Zone; 8, Vertical Relation of Deep-Seated Enrichment of Gold to Chalcocitization; 9, Vertical Relations of Silver-Gold and Gold-Silver Ore in Deposits Carrying Both Metals.

VI. REVIEW OF MINING-DISTRICTS, ... 805

Gold-Provinces of the United States, ... 806

1, Southern Appalachian Districts; 2, Black Hills, S. D.; 3, Treadwell Mine, Alaska; 4, Berner's Bay, Alaska; 5, Mother Lode District, Cal.; 6, Nevada City and Grass Valley, Cal.; 7, Ophir District, Cal.; 8, Silver Peak, Nev.; 9, Philipsburg, Mont.; 10, Other Montana Districts; 11, Edgemont, Nev.; 12, Leadville, Colo.; 13, Georgetown, Colo., Silver-Lead Deposits; 14, Auriferous Deposits of the Georgetown Quadrangle, Colo.; 15, San Juan, Colo.; 16, Cripple Creek, Colo.; 17, Summit District, Colo.; 18, Bodie, Cal.; 19, Exposed Treasure Mine, Cal.; 20, Tonopah, Nev.; 21, Goldfield, Nev.; 22, Manhattan, Nev.; 23, Annie Laurie Mine, Utah; 24, Bullfrog District, Nev.; 25, Gold Circle, Nev.; 26, Delamar Mine, Nev.

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I. Introduction and Summary.

Ferric iron, cupric copper, and manganitic manganese are present in many mineral waters, and under certain conditions any one of them will liberate chlorine from sodium chloride in acid solutions. Nascent chlorine dissolves gold. Each of these compounds will thus release chlorine at high temperatures, and at low temperatures in concentrated solutions. In cold, dilute solutions, ferric iron will not give nascent chlorine in appreciable quantity in 34 days, and cupric copper is probably even less efficient; but manganitic compounds (supplied by pyrolusite, etc.) liberate chlorine very readily. In a cold solution containing only 1,418 parts of chlorine per million, considerable gold is dissolved in 14 days when manganese is present. It should be expected, then, that those auriferous deposits, the gangues of which contain manganese, would show the effects of the solution and migration of gold more clearly than non-manganiferous ores.

Gold thus dissolved is precipitated by ferrous sulphate. It is, therefore, natural to suppose that gold in such solutions could not migrate far through rocks containing pyrite, since it would be quickly precipitated by the ferrous sulphate produced through the action of air, oxidizing waters, or the gold-solution itself, upon the pyrite. But the dioxide and higher oxides of manganese react immediately upon ferrous sulphate, converting it to ferric sulphate, which is not a precipitant of gold. Consequently, manganese is not only favorable to the solution of gold in cold, dilute mineral waters, but it also inhibits the precipitating action of ferrous salts, and thus permits the gold to travel further before final deposition.

These statements apply to the action of surface-waters descending through the upper parts of an auriferous ore-deposit, since such waters are cold, dilute, acid (*i.e.*, oxidizing) solutions. In deeper zones, where they attack other minerals, they lose acidity, until the manganese compounds, stable under oxidizing conditions, are precipitated together with the gold. Thus, manganite, as well as limonite and kaolin, is frequently found in secondary (*i.e.*, dissolved and reprecipitated) gold-ores. Moreover, in the precipitation of secondary copper and silver sulphides, ferrous sulphate is generally formed; and, consequently, the secondary silver or copper sulphides frequently contain gold.

Those deposits in the United States in which a secondary enrichment in gold is believed to have taken place are, almost without exception, manganiferous. Since secondary enrichment is produced by the downward migration, instead of the superficial removal and accumulation, of the gold, it should follow that both gold-placers and outcrops rich in gold would be found more extensively in connection with non-manganiferous deposits; and this inference is believed to be confirmed by field-observations.

The problem is not as simple as this preliminary statement of it may seem to indicate. Some of the numerous and complex data bearing upon it are collated and discussed in the pages that follow.

Among the papers which treat the superficial alteration and secondary enrichment of copper-, gold-, and silver-deposits, are those of S. F. Emmons,[1] Weed,[2] Penrose,[3] Winchell,[4] Van Hise,[5] Kemp,[6] and Rickard.[7] The processes upon which the changes depend are clearly outlined in these, and subsequent work has, in a large measure, confirmed the premises stated. The chemical laws and physical conditions controlling secondary enrichment have been reviewed in several reports more recently published and examples illustrating the processes have been multiplied. The papers of Lindgren, Ransome, Spencer, Boutwell, Irving, Graton, McCaskey, Spurr, and Garrey and Ball are particularly valuable. Such work has shown that the secondary enrichment of pyritic copper-deposits is an important and almost universal process; that many silver-deposits are enriched by superficial agencies; but that many gold-deposits do not show deep-seated secondary enrichment.

T. A. Rickard[8] has brought out clearly the processes by

[1] The Secondary Enrichment of Ore-Deposits, *Trans.*, xxx., 177 to 217 (1900).

[2] The Enrichment of Gold and Silver Veins, *Trans.*, xxx., 424 to 448 (1900).

[3] The Superficial Alteration of Ore-Deposits, *Journal of Geology*, vol. ii., No. 3, pp. 288 to 317 (Apr.–May, 1904).

[4] *Bulletin of the Geological Society of America*, vol. xiv., pp. 269 to 276 (1902).

[5] Some Principles Controlling the Deposition of Ores, *Trans.*, xxx., 27 to 177 (1900).

[6] Secondary Enrichment in Ore-Deposits of Copper, *Economic Geology*, vol. i., No. 1, pp. 11 to 25 (Oct.–Nov., 1905).

[7] The Formation of Bonanzas in the Upper Portions of Gold-Veins, *Trans.*, xxxi., 198 to 220 (1901).

[8] *Loc. cit.*

which gold-deposits may be enriched relatively near the surface in the oxidized zone by the removal of valueless minerals which are more readily dissolved than gold. On the problem of deeper-seated precipitation of gold below the zone of oxidation there is less evidence. In some mines, however, the transportation and deep-seated precipitation of gold is clearly shown, as was pointed out long ago by Weed.

While engaged in the investigation of certain auriferous deposits in the Philipsburg quadrangle, Montana, for the U. S. Geological Survey, I was confronted by evidence gained in two important mines, which seemed to be conflicting on this point. In one of them, the Cable mine, there was no evidence that gold had been concentrated by cold solutions below the zone of oxidation, but in the Granite-Bimetallic lode there was enrichment of both gold and silver below the zone of leached oxides. The richer silver-minerals occur in cracks and in small fissures cutting across the banding of the primary deposits and are related very distinctly to the present topography of the country. The evidence therefore appeared to be conclusive that these minerals were deposited by cold mineral waters and that their metallic contents had been dissolved from portions of the lode higher up. The enriched silver-ore carries considerably more gold than the primary ore in the bottom of the mine, and more than the upper portion of the oxidized zone, including the outcrop. No placers have been formed from this deposit, although it has produced considerable gold. On the other hand, important placers have been developed just below the outcrop at the Cable mine. Clearly there has been a kind of selection in the operation of the processes of solution and precipitation of gold.

Although the ores of the two deposits differ in other respects, the most striking difference is in the manganese-content. The abundance of manganese in the Granite-Bimetallic manifests itself in the characteristic coloration of the ores—pink in the unoxidized, brown or black in the oxidized zone. In the Cable, manganese is practically absent. The difference in manganese-content is so striking as to suggest a causal relationship with the equally-marked difference in the amount of secondary enrichment.

The use of manganese in the chlorination process to give

free chlorine, which dissolves gold, is well known. Le Conte[9] said as early as 1879 that free chlorine is the most important natural solvent of gold, and Richard Pearce, in his presidential address before the Colorado Scientific Society, in 1885, recorded experiments in which gold had been dissolved in hot sulphate solutions with common salt and manganese dioxide.[10] Don obtained similar results with more dilute solutions.[11] It appeared desirable, therefore, to ascertain whether these reactions are carried on appreciably in cold dilute solutions similar to mine-waters; and Nicholas Sankowsky and Clarence Russell, in a seminar on the Chemistry of Ore-Deposits, which I conducted at the University of Chicago, compiled all available analyses of waters from gold- and silver-mines in non-calcareous rocks. A. D. Brokaw conducted a series of experiments at my request, using cold dilute solutions of compositions suggested by the analyses. He performed other experiments also, showing the action of manganese dioxide on ferrous salts, which are applicable to the study of the precipitation of gold. During the progress of this investigation, W. J. McCaughey, of the Bureau of the Mint, Washington, D. C., published his valuable paper on the solvent effect of ferric and cupric salt solutions upon gold,[12] and this in a large measure supplemented the work carried on in the seminars at the University of Chicago.

The experiments conducted by Brokaw showed that manganese in the presence of chlorides and sulphates is very much more efficient in the reactions dissolving gold than are the other salts which are common in mine-waters. To verify these results by field-evidence, the review of the literature was taken up in greater detail, and there also the results indicate a marked difference in the behavior of the cold dilute mineral waters in the presence and in the absence of manganese. Lindgren's classification of the gold-deposits of North America has been of great value in reviewing these deposits; since in the United States manganese is rarely a gangue-mineral in the primary gold-deposits as old as the early Cretaceous California gold-veins, whereas it is frequently

[9] *Elements of Geology*, p. 285.

[10] *Proceedings of the Colorado Scientific Society*, vol. ii., p. 3 (1885-87).

[11] *Trans.*, xxvii., 654 (1897); p. 176, this volume.

[12] *Journal of the American Chemical Society*, vol. xxxi., No. 12, pp. 1261 to 1270 (Dec., 1909).

present in very appreciable quantities in those deposits which were formed nearer the surface and which are related to intrusives of Tertiary age. Possibly this difference is due to conditions of temperature and pressure which prevailed when the deposits were formed.[13] Since there are no data which show the effect of highly-carbonated waters on these reactions, I have as far as possible eliminated examples of gold-deposits in limestone, and the discussion is confined mainly to deposits in non-calcareous rocks. I have not attempted to review exhaustively the evidence afforded by deposits outside of the United States with respect to the hypothesis suggested, but some of these deposits appear to supply accurate confirmatory data.

In a statistical study of outcrops, to ascertain whether gold is more extensively leached in manganiferous lodes than in the outcrops of those which do not carry manganese, and whether placers are more frequently developed in connection with non-manganiferous lodes, the reports of Dr. R. W. Raymond,[14] written soon after the discoveries of many of the deposits, have been of great value.

I wish to acknowledge my indebtedness to my colleagues of the U. S. Geological Survey, and to many other geologists whose accurate observations I have drawn upon to test the hypothesis. Their conclusions respecting the secondary enrichment of gold appear to support the hypothesis, and, differing as they do with respect to the migration of gold in particular deposits, they become reconciled when inspected from this view-point, and thus they are themselves supported. Dr. R. C. Wells, of the U. S. Geological Survey, has read critically certain portions of this paper, where the principles of physical chemistry are involved.

II. Salts Contained in the Waters of Gold- and Silver-Mines in Non-Calcareous Rocks.

The composition of mine-waters depends upon the character of the ore and wall-rock and the position of the deposit with respect to bodies of salt water. There are certain compounds which are generally present, and some which nearly always predominate. Of the few analyses which have been made of

[13] W. Lindgren, The Relation of Ore-Deposition to Physical Conditions, *Economic Geology*, vol. ii., No. 2, pp. 105 to 127 (Mar.–Apr., 1907).

[14] *Mines and Mining West of the Rocky Mountains* (1868–1875).

waters from gold-mines, a large proportion are incomplete; and it is not always stated whether compounds not reported were looked for. Sankowsky and Russell, utilizing all data available to them, recalculated the analyses to the ionic form of statement, and where necessary to parts per million, and made a general average of the results. Where compounds were not reported in the analyses it was assumed that they were not present. Arsenic, antimony, and other elements, small traces of which must be present in some waters, are not reported. Since the averages were obtained by dividing the sums by the total number of analyses (29) and not by the number of analyses showing a particular element, and since some analyses are incomplete, any corrections applied for this source of error would tend to increase the number of parts per million indicated. On the other hand, some of the mine-waters were taken from places protected from the more active vadose circulation, and are clearly more concentrated than the major part of the waters. The average of analyses, although a rude approximation, is useful, since it gives some quantitative value to their factor in the problem, and indicates the general nature of the cold solutions in which the metals are transported.

TABLE I.—*Average of 29 Analyses of Waters taken from Gold-, Silver-, and Gold-Silver Mines in Non-Calcareous Rocks.*
(Compiled by N. Sankowsky and C. Russell.)

	Parts Per Million.	Number of Determinations.	Absent or Not Determined.
Cl^a	873.10	22	7
SO_4	7,292.29	13	16
CO_3	77.59	7	22
$NO_3{}^a$	0.06	1	28
PO_4	0.00	traces in 2	27
SiO_2	34.94	12	17
K	17.25	7	22
Na^a	261.20	9	20
Li	0.10	1	28
Ca	295.00	11	18
Sr	0.06	1	28
Mg	242.44	9	20
Al	333.65	6	23
Mn	30.91	6	23
Ni	trace	traces in 3	26
Co	trace	traces in 3	26
Cu	5.09	2	27
Zn	2.70	5	24
Fe^{II}	277.66	22	7
Fe^{III}	603.07	25	4
H (in acids)	97.26	10	19

[a] Probably too high (see discussion).

1. *Sulphates.*

Primary gold-ores generally carry pyrite, which, oxidizing at or near the surface, yields ferrous sulphate, ferric sulphate, and sulphuric acid. The acid is not formed directly from galena, PbS, or from zinc-blende, ZnS, but pyrite, FeS_2, carries more sulphur than is required to supply SO_4 radical to satisfy the iron, even if ferric sulphate, $Fe_2(SO_4)_3$, is formed instead of $FeSO_4$. As lately shown by Buehler and Gottschalk,[15] galena and zinc-blende dissolve very much more slowly in the absence of FeS_2. The reaction probably requires free acid, which the iron sulphide, owing to its excess of sulphur, supplies. The sulphuric acid from pyrite is increased also by the hydrolization of ferric sulphate and the deposition of limonite.

In Table I. the sulphate radical (7,292 parts per million) is nearly ten times as abundant as all other negative ions and is also in excess of bases, so that on any basis of adjustment to form salts much H_2SO_4 remains. The table shows also an average of 97.26 parts per million of hydrogen in acid. In view of the low atomic weight of hydrogen, this indicates the strongly acid character of the solutions.

2. *Chlorides.*

Chlorine is present in most mine-waters. In 22 out of the 29 analyses it is reported as traces or as determined quantities. The average of 29 analyses shows 873 parts per million, but if the one abnormally-rich sodium-chloride water of Silver Islet, Lake Superior, is excluded, the remaining 28 analyses show but 111 parts per million. This figure is probably a better average. It would be further reduced some 2 or 3 parts by excluding the waters of the Geyser mine, Silver Cliff, Colo., which may have come from a deep source. With these two exceptions, it is noteworthy that the waters from mines remote from salt water contain less chlorine than those near the sea or in undrained areas. The distribution of chlorine is an important element in the migration of gold, and therefore I shall consider the sources of chlorine in some detail.

The salt in sedimentary rocks may be dissolved by groundwater. From the available analyses it appears that this source is of less importance than would be supposed. The chlorine-

[15] *Economic Geology*, vol. v., No. 1, p. 30 (Jan., 1910).

content of composite samples of 78 shales and of 253 sandstones was only a trace, while an analysis of a composite of 345 limestones showed only 0.02 per cent.[16] A few rock-making minerals, such as chlor-apatite, scapolite, haüyne, and nosean, contain combined chlorine; but of these all but apatite occur mainly in very rare types of rocks. In some rocks chlorine is present probably as NaCl in the solid particles contained in fluid inclusions. The work of R. T. Chamberlin, A. Gautier, and others has shown that many granular igneous rocks, when heated to high temperatures, give off gases equal to several times their own volume. While further inquiry of this character is desirable, it is probably true that in general but little chlorine is present in such gases. But gases from certain volcanic rocks, such as obsidian, often contain a high proportion of chlorine and chlorides. Albert Brun[17] has shown that some of the Krakatoa lavas contain gases which equal about one-half the volume of the rock, and that more than half of such gases consists of chlorine, hydrochloric acid, and sulphur monochloride.

Apatite, though widespread in igneous rocks, is a very stable mineral, and consequently cannot be looked upon as an important source of chlorine, although it may contribute small amounts when exposed to favorable conditions of weathering. The average chlorine-content of igneous rocks is, according to F. W. Clarke, 0.07 per cent.

Chlorine is present in nearly all natural waters. Its chief source is from finely-divided salt or salt water from the sea and from other bodies of salt water. The salt is carried by the wind and precipitated with rain.[18] The amount of chlorine in natural waters varies with remarkable constancy with the distance from the shore; several determinations very near the seashore show from 10 to 30 parts of chlorine per million; a few miles away it is generally about 6 parts per million; 50 miles from shore it is generally less than 1 part per million. A surface-

[16] F. W. Clarke, *Bulletin No.* 330, *U. S. Geological Survey*, p. 27 (1908).

[17] Quelques Recherches sur le Volcanisme aux Volcans de Java. Cinquième partie. Le Krakatau. *Archives des Sciences physiques et naturelles*, Genève, vol. xxviii., No. 7 (Juillet, 1909).

[18] D. D. Jackson, The Normal Distribution of Chlorine in the Natural Waters of New York and New England, *Water Supply and Irrigation Paper No.* 144, *U. S. Geological Survey* (1905).

water from a reservoir at Leadville contained 1.14 parts of Cl per million.[19] The isochlores parallel the shore-line with great regularity, as indicated in the map, Fig. 1, taken from Jackson's report. The amount of chlorine contributed from this source even near the seashore appears small (from 6 to 10 parts per million); but it may be furthur concentrated in the solutions by evaporation or by reaction with silver, lead, etc., forming chlorides, which in the superficial zone may subsequently be changed to other compounds. In arid countries, as suggested by C. R. Keyes, dust containing salt doubtless contributes chlorine to the mine-waters. Penrose,[20] discussing the distribution of the chloride ores, pointed out long ago that these minerals form most abundantly in undrained areas.

3. *Carbonates and Alkaline Earths.*

The analyses in Table I. do not include those from mines in limestones. The carbonate reported gives an average of 77 parts per million. In the acid waters under consideration, the carbonates of the bases would necessarily be present as bicarbonates, although this fact is not indicated in the analyses.

Even in non-calcareous rocks considerable calcium (295 parts per million) and magnesium (242 parts) are carried by the waters. They are derived in part from reactions between the acid sulphates and the silicates of the wall-rock.

4. *Alumina.*

In some waters aluminum sulphate is abundant (the average of aluminum, 333 parts per million). It forms where sulphate waters attack kaolin, setting free SiO_2 and taking alumina into solution. The above average is probably high on account of one concentrated alum-water in a Comstock mine.[21]

5. *Nitrates.*

Nitrates are not abundant in mine-waters. In one analysis only[22] is NO_3 reported (1.60 parts per million), and this in a deep-seated water of questionable genesis.

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[19] S. F. Emmons, Geology and Mining Industry of Leadville, Colorado, *Monograph No. XII., U. S. Geological Survey*, p. 552 (1886).

[20] *Journal of Geology*, vol. ii., No. 3, p. 314 (April–May, 1894).

[21] *Bulletin of the Department of Geology, University of California*, vol. iv., No. 10, p. 192 (1904–06).

[22] Geyser Mine, Silver Cliff, Colo. See S. F. Emmons, *Seventeenth Annual Report, U. S. Geological Survey*, Part II., p. 462 (1895–96).

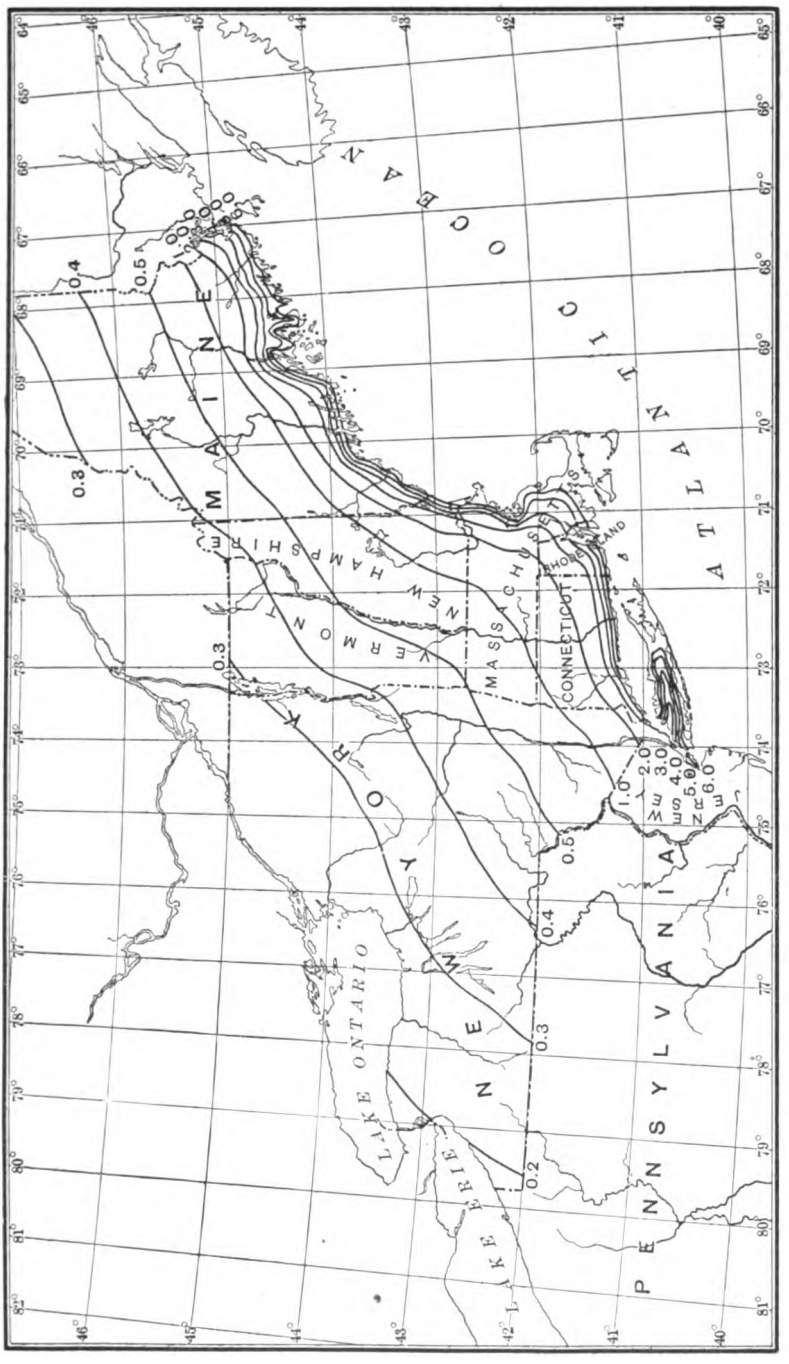

FIG. 1.—NORMAL CHLORINE MAP OF NEW ENGLAND AND NEW YORK.
The numbers on the isochlores indicate the parts of chlorine per million in the natural waters.
(Compiled by Daniel D. Jackson, U. S. Geological Survey, *Water Supply and Irrigation Paper No. 144.*)

6. *Phosphates.*

Traces only of PO_4 are reported from two mine-waters; others contained none, if determinations were made.

7. *Silica.*

Silica (35 parts per million) appears high for acid waters. The analyses include a manganiferous sulphate water from the Comstock, abnormally high in silica.[23]

8. *Iron.*

Iron is the most abundant metal in the waters of gold-mines. Ferric iron (603 parts per million) is, according to these analyses, more than twice as abundant as ferrous iron (277 parts per million). Probably too little attention has been given to the state of oxidation of iron in unaltered mine-waters. Ferrous salts in solution, when exposed to air, rapidly become ferric; yet, so far as I know, no mine-water which has clearly not had access to air has been examined with respect to the state of oxidation of the iron. Ferrous iron is much more abundant below than above the water-table.

9. *Manganese.*

If manganiferous minerals are present in the primary ore, they oxidize in the upper portion of the deposit to manganese dioxide or other high oxides of manganese; and these, in turn, oxidize ferrous sulphate, in the presence of sulphuric acid, to ferric sulphate. Consequently, the iron in manganiferous waters is likely to be in the oxidized state.

10. *Copper.*

One analysis shows 147 parts of copper per million. Two other analyses show traces. Small amounts must be present in many other waters, since gold-ores often carry copper. Possibly, small traces of the heavy metals were not looked for in many of the waters analyzed.

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[23] *Bulletin of the Department of Geology, University of California*, vol. iv., No. 10, p. 192 (1904–06).

III. Chemical Experiments in the Solution and Deposition of Gold.

The superficial alteration of gold-deposits and the migration of gold in the deposits take place at low temperatures. At the very surface the temperatures range between 0° and 50° C. and pressures do not exceed one atmosphere. At the normal gradient of increase, the temperatures, even several thousand feet below water-level, would not exceed 100° C., and in the main are considerably lower. The general character and, approximately, the concentration of the solutions are known from the analyses of mine-waters. The conditions are fairly constant. From the mass of chemical data relating to the subject, the following experiments seem to be particularly suggestive in connection with the present problem.

1. Stokes[24] placed gold leaf in a solution containing 25 g. per liter of ferric sulphate, and, after heating to 200° C., found that not a trace of gold had been deposited in the cold part of the sealed tube in which the experiment was carried on. This experiment does not confirm the statement frequently made that ferric sulphate will dissolve gold.

2. Don[25] exposed to air finely-divided gold and auriferous sulphide ores in solutions containing from 1 to 20 g. of ferric chloride and ferric sulphate per liter of water; and after several months no gold had been dissolved. Presumably the gold was not mixed with the sulphide in all of the experiments.

3. W. J. McCaughey,[26] upon boiling for several hours 50 cc. of HCl (sp. gr. 1.178) diluted to 125 cc. with 250 mg. of gold, found there was no loss of gold.

4. In a bent tube Stokes[27] heated gold leaf for 16 hr. at 200° C. in a solution composed of 85 g. of cupric chloride and 133 cc. of 20 per cent. HCl in a liter of water. The gold leaf was dissolved and redeposited in the upper portion of the tube. He writes the reaction as follows:

$$Au + 3\ CuCl_2 \leftrightharpoons AuCl_3 + 3\ CuCl.$$

[24] *Economic Geology*, vol. i., No. 7, p. 650 (July–Aug., 1906).

[25] *Trans.*, xxvii., 598 (1897); p. 173, this volume.

[26] *Journal of the American Chemical Society*, vol. xxxi., No. 12, p. 1263 (Dec., 1909).

[27] *Op. cit.*, vol. i., p 649.

5. Stokes[28] heated gold leaf to 200° C. in a closed tube containing a solution of 25 g. of ferric sulphate and 0.01 g. of NaCl. Gold was dissolved in 40 hours.

6. Stokes[29] found that at 200° C. gold leaf was dissolved in a mixture of 2 parts of 20 per cent. solution of ferric chloride and 1 part of 20 per cent. solution of HCl.

7. W. J. McCaughey[30] dissolved gold at from 38° to 43° C., in hydrochloric acid solutions of ferric sulphate. The results are indicated by the curves in Fig. 2. Solution *A* contained 1 g. of iron, introduced as ferric sulphate, and 25 cc. of HCl (sp.

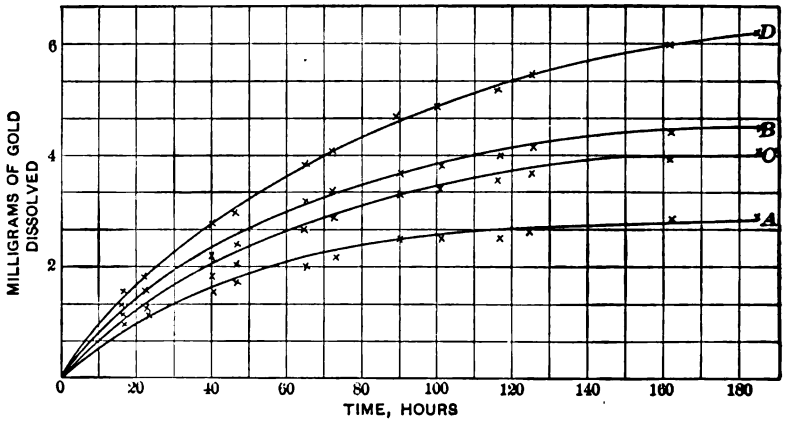

FIG. 2.—DIAGRAM SHOWING THE RATE OF SOLUTION OF GOLD IN CONCENTRATED SOLUTIONS OF HYDROCHLORIC ACID AND FERRIC SULPHATE. (Illustrating Experiment No. 7, by McCaughey.)

gr. 1.178) in a solution diluted to 125 cc. containing 250 mg. of gold rolled to 0.009 in. Solution *B* contained the same amount of iron sulphate and 50 cc. of HCl. Solution *C* contained 2 g. of Fe as ferric sulphate and 25 cc. of HCl. Solution *D* had twice the concentration of *A*. The diagram shows the amount of gold dissolved after different periods of treatment.

8. McCaughey[31] found that gold is dissolved at from 38° to 43° C. in a strong solution of cupric chloride and HCl. The

[28] *Economic Geology*, vol. i., No. 7, p. 650 (July–Aug., 1906).

[29] *Idem*, p. 650.

[30] *Journal of the American Chemical Society*, vol. xxxi., No. 12, p. 1263 (Dec., 1909).

[31] *Idem*, p. 1264.

amounts dissolved are shown by the curves in Fig. 3. Solution *A* contained 1 g. of Cu as cupric chloride and 25 cc. of HCl (sp. gr. 1,178); solution *B*, 1 g. of Cu as $CuCl_2$ and 50 cc. of HCl; solution *C*, 2 g. of Cu as $CuCl_2$ and 25 cc. of HCl; and solution *D*, 2 g. of Cu as $CuCl_2$ and 50 cc. of HCl; the final solution being in all cases diluted to the volume of 125 cc. The diagram shows that *D*, which was twice as concentrated as *A*, dissolved about 12 times as much gold.

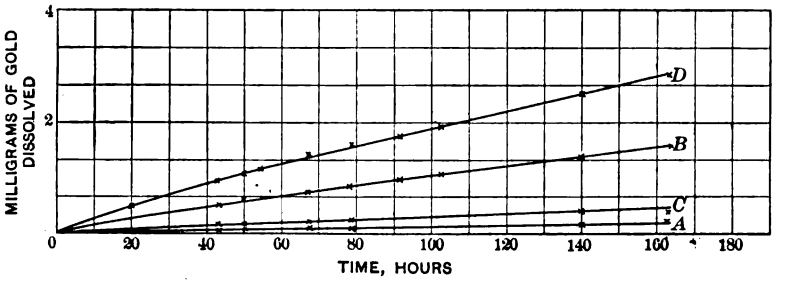

FIG. 3.—DIAGRAM SHOWING THE SOLUBILITY OF GOLD IN CONCENTRATED SOLUTIONS OF HYDROCHLORIC ACID AND CUPRIC CHLORIDE.
(Illustrating Experiment No. 8, by McCaughey.)

9. Richard Pearce[32] placed native gold in a flask containing hydrated manganese dioxide with 40 g. of salt and 5 or 6 drops of H_2SO_4. After heating for 12 hr. appreciable gold had been dissolved.

10. T. A. Rickard[33] extracted 99.9 per cent. of the gold from rich manganiferous ore with a solution of ferric sulphate, common salt, and a little H_2SO_4.

11. Don[34] found that 1 part of HCl in 1,250 parts of H_2O, in the presence of MnO_2, dissolves appreciable gold.

A number of experiments on the solubility of gold in cold dilute solutions were made at my request by A. D. Brokaw.[35] The nature of these experiments is shown by the following statements, in which (*a*) and (*b*) represent duplicate tests:

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[32] *Trans.*, xxii., 739 (1893).
[33] *Trans.*, xxvi., 978 (1896).
[34] *Trans.*, xxvii., 599 (1897); p. 175, this volume.
[35] *Journal of Geology*, vol. xviii., No. 4, pp. 321 to 326 (May–June, 1910).

12. $Fe_2(SO_4)_3 + H_2SO_4 + Au.$
    (*a*) no weighable loss. (34 days.)
    (*b*) no weighable loss.

13. $Fe_2(SO_4)_3 + H_2SO_4 + MnO_2 + Au.$
    (*a*) no weighable loss. (34 days.)
    (*b*) 0.00017 g. loss.[c]

c This duplicate was found to contain a trace of Cl, which probably accounts for the loss.

14. $FeCl_3 + HCl + Au.$
    (*a*) no weighable loss. (34 days.)
    (*b*) no weighable loss.

15. $FeCl_3 + HCl + MnO_2 + Au.$
    (*a*) 0.01640 g. loss. Area of plate, 383 sq. mm. (34 days.)
    (*b*) 0.01502 g. loss. Area of plate, 348 sq. mm.

In each experiment the volume of the solution was 50 cc. The solution was one-tenth normal with respect to ferric salt and to acid. In experiments 13 and 15, 1 g. of powdered manganese dioxide was also added. The gold, assaying 999 fine, was rolled to a thickness of about 0.002 in.; cut into pieces of about 350 sq. mm. area, and one piece, weighing about 0.15 g., was used in each duplicate.

To approximate natural waters more closely, a solution was made one-tenth normal as to ferric sulphate and sulphuric acid, and one twenty-fifth normal as to sodium chloride. Then 1 g. of powdered manganese dioxide was added to 50 cc. of the solution, and the experiment was repeated. The time was 14 days.

16*a*. $Fe_2(SO_4)_3 + H_2SO_4 + NaCl + Au.$
No weighable loss.

16*b*. $Fe_2(SO_4)_3 + H_2SO_4 + NaCl + MnO_2 + Au.$
Loss of gold, 0.00505 gram.

The loss is comparable to that found in experiment 15, allowing for the shorter time and the greater dilution of the chloride.

To determine whether the free acid or the ferric chloride is

the solvent, experiment 17 was made, in which 50 cc. of one-tenth normal HCl was used with 1 g. of powdered MnO_2.

17. $HCl + MnO_2 + Au$.
Loss of Au, 0.01869 g. Time, 14 days.

In experiment 18, sodium hydroxide was added to 50 cc. of one-tenth normal ferric chloride solution until the precipitate

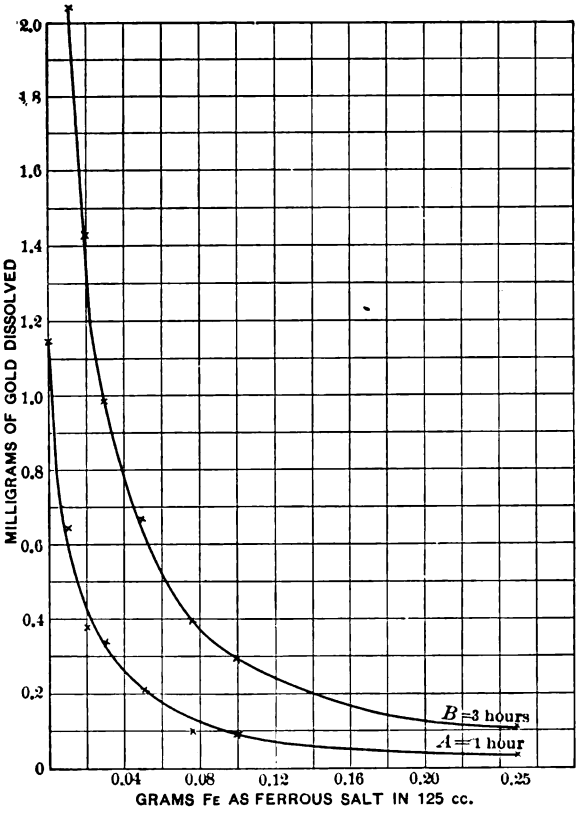

FIG. 4.—DIAGRAM ILLUSTRATING THE EFFECT OF FERROUS SULPHATE IN SUPPRESSING THE SOLUBILITY OF GOLD IN FERRIC SULPHATE SOLUTIONS, WHERE GOLD IS DISSOLVED AS CHLORIDE.

(Illustrating Experiment No. 19, by McCaughey.)

formed barely re-dissolved on shaking, after which 1 g. of powdered MnO_2 was added.

18. $FeCl_3 + MnO_2 + Au$.
Loss of Au, 0.00062 g. Time, 14 days.

These results show, that in the presence of manganese dioxide, free hydrochloric acid is more efficient than ferric solutions.[36]

19. McCaughey's experiments show the effect of very small amounts of ferrous sulphate on solutions of gold in ferric sulphate. To a solution, 125 cc., containing 1 g. of iron as ferric sulphate and 25 cc. of HCl, ferrous sulphate was added in quantities containing from 0.01 to 0.25 g. of ferrous iron. The solutions were immersed in boiling water and subsequently 250 mg. of gold was added. The dissolved gold was determined at the end of 1 hr. and 3 hr. At the end of 3 hr. the gold dissolved was greater, probably because some ferrous sulphate had changed to ferric sulphate. Even 0.01 g. of the ferrous iron greatly decreases the solubility of gold in the ferric sulphate and HCl solution, and 0.25 g. of ferrous sulphate drives nearly all the gold out of solution. These experiments are illustrated by Fig. 4, in which the horizontal lines represent ferrous salt put in the mixture and the vertical lines the amount of gold (in milligrams) dissolved by chlorine in the solution. The lower curve represents conditions at the end of 1 hr., the upper curve at the end of 3 hr., when some of the ferrous salt had oxidized by contact with the air.

20. To determine the rate at which ferrous sulphate, in the presence of sulphuric acid and manganese dioxide, would be oxidized to the ferric salt, Brokaw made the following experiment:

100 cc. of 1.6 normal $FeSO_4$ was acidified with sulphuric acid and shaken vigorously with 5 g. of powdered MnO_2. After 5 min., the solution was filtered. No ferrous iron was detected by the ferricyanide test, showing that the iron had been completely oxidized to the ferric state.

IV. Discussion of Experiments.

1. *Nitrates.*

Dilute acid nitrate-chloride waters readily dissolve gold, since they are equivalent to weak aqua regia. The chlorine

[36] Brokaw, *Journal of Geology*, vol. xviii., No. 4, pp. 322 to 323 (May–June, 1910).

set free by the reaction oxidizing HCl is more active than a solution of chlorine in water, and converts gold into gold chloride. For present purposes we may consider that the reaction is as follows:

$$9\ HCl + 3\ HNO_3 + 2\ Au \rightarrow 6\ H_2O + 3\ NOCl + 2\ AuCl_3.$$

Nitrosyl chloride, NOCl, which is formed in this reaction, does not react directly with gold, but is thought by some to affect the reaction favorably as a catalytic agent. Whether this is true or not, in each of the reactions by which gold is dissolved in chloride solution its solvent power may be ascribed to its "nascent" state. In this reaction, as in those which follow, the presence of an element with more than one valence is a necessary condition, and its valence is reduced as gold passes into solution.

The reaction given above, $3\ HCl + NHO_3$, may be written as follows:[37]

$$Cl - \boxed{H + H - O -} \overset{\overset{O}{\|}}{N} \boxed{= O + 2\,H}\ Cl \rightarrow 2\ H_2O + Cl_2 + Cl - N = O.$$

The chlorine reacts with gold, forming soluble gold chloride.

$$2\ Au + 3\ Cl_2 \rightarrow 2\ AuCl_3.$$

With regard to the latter reaction, Dr. R. C. Wells, of the U. S. Geological Survey, supplied the following note:

"The reaction ($2\ Au + 3\ Cl_2 \rightarrow 2\ AuCl_3$) aims to express the initial and final stages, but says nothing of the mechanism of the reaction or the necessity for the chlorine being in the 'nascent' state. In accordance with present theories, a 'nascent' chlorine atom, while taking a negative charge to form chloride, allows the corresponding positive charge to ionize the gold,

$$Au + \odot = Au^{\bullet}.$$

This ionization occurs with greater difficulty in the case of gold than with almost any other metal. The aurous ion passes with great readiness into the auric ion, $Au^{\bullet\bullet\bullet}$. Moreover, both ions form complexes with chlorides. The effectiveness of

[37] Alexander Smith, *General Inorganic Chemistry*, p. 449 (1907).

chlorine in dissolving gold in accordance with this theory may be ascribed partly to the production of the complex gold chloride ions, thus removing the gold ions from solution with such effectiveness that more gold ionizes, and thus the process continues until equilibrium is established."

In the 29 analyses of mine-waters NO_3 is reported from but one (Geyser mine, Silver Cliff, Colo., 1.6 parts per million), and this is a water of questionable genesis. Possibly, nitrates are more abundant than is indicated by the analyses; and if so, they must increase the solvent power of chloride solutions; but the data at present available do not indicate that they affect the superficial reactions to any important extent.

2. *Manganese Oxides.*

That gold is dissolved in moderately dilute solutions containing salt and manganese oxides is shown by experiments 11, 15 and 16. The reaction with manganese used to prepare chlorine commercially is illustrated by the following equation: (The reaction is not so simple as stated. It is discussed later.)

$$Mn^{iiii}O_2 + 2\,NaCl + 3\,H_2SO_4 \rightarrow 2\,H_2O + 2\,NaHSO_4 + Mn^{ii}SO_4 + 2\,Cl.$$

At the beginning of the reaction the manganese has a valence of four; at the end a valence of two. With acid the reaction may be as follows:

$$MnO_2 + HCl \rightarrow 2\,H_2O + MnCl_2 + Cl_2.$$

Besides the presence of a chloride, some other conditions are essential to the solution of gold. There appear to be two. One is that some other substance must also be present which is capable of being reduced so as to liberate chlorine—as, for example, a ferric salt which may be reduced to the ferrous, a cupric to the cuprous, the higher manganese salts to the lower, etc. The other is the evolution of "nascent" chlorine. This is particularly illustrated by the action of aqua regia or the production of chlorine by hydrochloric acid and pyrolusite. In short, any of a number of methods of producing free chlorine would be effective in the solution of gold. Possibly both of the conditions just mentioned may in the last analysis be identical.

The essential point is that the atomic chlorine in a state of molecular exchange or evolution is able to combine with the gold. For present purposes the gold may be considered to dissolve as gold chloride, although chemical investigations favor the theory that a complex ion containing gold is formed. The only consideration which becomes important in its geological aspect is the presence of the compounds which not only admit of easy changes of valence, but which act upon hydrochloric acid with the production of free chlorine.

In mine-waters chlorine is supplied as NaCl.

16*b*. $Fe_2(SO_4)_3$ + H_2SO_4 + NaCl + MnO_2 + Au
N/10 N/10 N/25 1 g. 0.15 g.
0.00505 g. loss of gold by solution in 14 days (cold).

Under the same conditions without manganese there was no weighable loss (see experiment 16*a*).

As used herein the normal solution contains 1 g.-equivalent of the solute in 1 l. of solution. A solution normal with respect to chlorine contains 1 g. of chlorine times 35.45, the molecular weight of chlorine, in 1 l. of solution.

In this experiment the concentration of Cl (1,418 parts per million) is not so great as has been observed in a few mine-waters, and not more than three times as great as Don determined in waters from a number of Australasian mines.[38] The solutions, however, contain more chlorine than the average of 29 analyses of mine-waters (873 parts of Cl per million), considerably more than that of 28 analyses (111 parts of Cl per million), and more than most mine-water analyses from American gold-mines.

Manganese is abundant in many gold-bearing deposits; is sparingly represented in some; and from a very large number it has not been reported. The chief primary minerals are the carbonates (rhodochrosite and manganiferous calcite), the silicate (rhodonite), amethystine quartz, and the less abundant sulphite, alabandite. Some rock-making minerals carry small amounts of manganese. It readily forms sulphates, chlorides, etc., and is dissolved by acid mine-waters. In the 29 analyses of Table I. it is reported from 6 mines. In some waters it is

[38] *Trans.*, xxvii., 654 (1897); p. 176, this volume.

abundant. The average of the 29 shows 30.9 parts per million. Even a little manganese generally stains the gossan black or chocolate-brown, and consequently it is readily recognized in the oxidized ores. Manganese changes its valence more readily than other elements common in gold-ores and it is in many respects unique among the elements. The following note is abridged from Alexander Smith, *General Inorganic Chemistry*, p. 737:

It stands on the left side of the eighth column of the periodic table; the right side of that column is occupied by the halogens. It is never univalent as the halogens are; but the heptoxide, Mn_2O_7, and corresponding permanganic acid, $HMnO_4$, are in many ways closely related to the heptoxide of chlorine and perchloric acid, $HClO_3$. Permanganic acid is a very active acid. Contrary to the habit of feebly acidic and feebly basic oxides such as those of zinc, aluminum and tin, the basic oxides of manganese are not at all acidic and the acidic oxides, with the possible exception of Mn_2O_3, are not also basic. There are thus five rather well defined sets of compounds showing five different valences of the element.

These include manganosite (MnO), pyrochroite ($MnO.H_2O$), manganite ($Mn_2O_3.H_2O$), hausmannite (Mn_3O_4), pyrolusite (MnO_2), psilomelane, etc.

3. *Lead Oxides.*

Lead oxide, like manganese oxide, is said to facilitate the solution of gold[39] when added to solutions of ferric sulphate and sodium chloride. Lead is both bivalent and quadrivalent and forms corresponding oxides and hydroxides. These, however, are generally not abundant in the oxidized zones of lead-bearing ore-deposits, probably because the lead carbonate and the sulphate are relatively insoluble in water and usually are formed instead of the oxides. Lead is reported in but one of the 29 analyses of water from gold- and silver-mines, tabulated above, and in this case the water carried but 1.35 parts per million. Many gold-deposits contain but little lead and some contain none. It is believed to be of very subordinate importance in connection with the solution of gold.

4. *Ferric Compounds.*

As shown by experiments, gold is not dissolved by hydrochloric acid, by ferric sulphate, or by ferric chloride. It is

[39] Victor Lehner, *Journal of the American Chemical Society*, vol. xxvi., No. 5, p. 552 (May, 1904).

dissolved at 38° C. in concentrated solution containing both ferric sulphate and hydrochloric acid.

5. *The Efficiency of Ferric Iron and Cupric Copper to Supply Nascent Chlorine, Compared with that of Manganitic Manganese.*

As shown by experiment 4, a concentrated solution of $CuCl_2$ with HCl dissolves appreciable gold at 200°, and Fig. 3 shows that a solution containing 1 g. of copper as cupric chloride and 25 cc. of HCl (sp. gr., 1.178) in 125 cc. of solution at 38° +, dissolves 0.23 mg. of gold in 163 hr. Since cupric copper and ferric iron are present in many mineral waters, the nature of these reactions should be considered in some detail in order to compare their efficiency with that of manganitic manganese.

Solutions of ferric sulphate with sulphuric acid and salt dissolve gold at high temperatures. Concentrated solutions of ferric sulphate and hydrochloric acid dissolve gold at from 38° to 43° C. In the cold, the reaction may go on in concentrated solutions, but in those approximating the concentration of mine-waters (and one of them considerably more concentrated than most mine-waters) no weighable loss of gold was obtained. With MnO_2 under the same conditions there was a very appreciable loss in a solution containing only 1.4 g. of Cl in a liter. It appears, therefore, that the action of ferric iron on gold in cold dilute mine-waters with H_2SO_4 and NaCl is probably negligible; for the experiments with ferric iron in such solutions, without manganese, extended over a period of 34 days without weighable loss of gold.

Many auriferous deposits contain copper; and it is desirable to compare the efficiency of cupric with ferric salts and with manganitic salts in similar solutions. Since the reactions which give nascent chlorine are conditioned upon the presence of some element that changes its valence in the reactions, and since the processes underground take place in sulphate solutions, it did not appear necessary, after ferric salt had been shown to be incompetent, to conduct experiments with copper; for, as is well known, cuprous salts, though they may be present, have never been detected in acid sulphate mine-waters, whereas ferric and ferrous sulphate are very common in such waters.

Fig. 2 shows that in 163 hr. a solution carrying 2 g. of ferric iron as sulphate and 50 cc. of HCl (sp. gr. 1.178) diluted to 125 cc., with 250 mg. of gold in the solution, dissolves 6 mg. of gold. In the same time, as shown by Fig. 3, a solution containing 2 g. of copper as cupric chloride and 50 cc. of HCl diluted to 125 cc., dissolves but 2.84 mg. of gold, the same amount of gold being exposed. These results indicate that, in concentrated solutions at least, cupric salt is less efficient than ferric salt. Comparing the details of the curves, however, it appears that the reaction with ferric salt is probably near a state of equilibrium; but the experiment with cupric salt suggests that, given a longer time, considerably more gold may be dissolved. It cannot be concluded, therefore, that the solvent action of a cupric salt would be less than that of a ferric salt, if a very much longer time were allowed to lapse before the loss of gold in the two experiments was ascertained, although the experiments suggest that this is probable.

The curves of Fig. 3 show that a dilution of the concentrated solution of cupric chloride and hydrochloric acid greatly decreases the amount of gold dissolved under the same conditions. For example, the solution containing 2 g. of copper as cupric chloride and 50 cc. of HCl (sp. gr. 1.178) dissolved 2.84 mg. of gold in 163 hr. Under the same conditions a solution of the same salts, but of one-half the concentration, dissolved only 0.23 mg. of gold in 163 hr. It thus appears that a dilution of the solution to one-half decreases its solvent action (2.84 divided by 0.23) to about one-twelfth. If the solvent were diluted to approximately the strength of mine-waters, it should be expected that the efficiency of cupric salt in these reactions would be almost immeasurably decreased. Indeed, the lower curve, *A*, in Fig. 3, strongly suggests this, and indicates also that the reaction with cupric salt at this concentration is nearing completion; for about half as much gold (0.11 mg.) was dissolved by this solution in 66 hr. as was dissolved in 163 hr. (0.23 mg.). It is improbable that the character of this curve would greatly change if the reaction continued over a period twice as long, and, projecting the curve to 14 days, in order that the solvent action of cupric salt may be compared with that of manganitic salt, it appears that in 14 days 0.48 mg. of gold would be dissolved in waters of this concentration, assum-

ing that the gold dissolved is in proportion to the time exposed, thus giving the advantage to cupric salt. The experiments with MnO_2 were carried on at about 18° C., and those with cupric salt at from 38° to 45° C.

The gold dissolved (experiment 16*b*) in the dilute solution with manganese was more than 10 times as much as that dissolved with the cupric salt (experiment 8). The hydrochloric acid (sp. gr. 1.178) with cupric chloride contained 34.99 per cent. of HCl and 34 per cent. of Cl. Disregarding the Cl introduced by cupric chloride, the solution used (25 cc. diluted to 125 cc.) contained 6.8 per cent. of Cl. The solution with manganese dioxide (one-twenty-fifth normal) contained but 0.14 per cent. of Cl. The chlorine (in acid) in the experiment with copper was thus 49 times as much as the total chlorine in the experiment with manganese.

The amount of solution used in experiment 8, with cupric salt, was 2.5 times as much as the amount of solution used in experiment 16*b*, with manganese, but the area of gold exposed was not so great. In experiment 8, the gold was rolled to a thickness of 0.009 in. and cut into 1-mm. squares, whereas that used in experiment 16*b* was rolled to a thickness of 0.002 in., exposing areas of about 350 sq. mm. In the experiment with copper 250 mg. of gold was introduced, whereas only 150 mg. was introduced in experiment 16*b*. Correcting for areas exposed, a cupric solution 50 times as concentrated as the manganitic solution with respect to chlorine will dissolve about one-fifth as much gold where equal areas are exposed. In other words, the action with manganese appears to be more than 250 times as efficient as with cupric salt, even if it is assumed that further dilution would not decrease the solvent action of cupric salt in a geometrical ratio, as is indicated by the curves in Fig. 3. Comparing the end-points of curves *A* and *D*, Fig. 3, it is seen that a dilution of the solution to one-half decreases the solvent action with cupric salt to about one-twelfth. If further dilution to one-twenty-fifth normal HCl decreases the solvent action with cupric salt in this ratio, then the efficiency of the solution with cupric salt would be about $\frac{1}{1\,000\,000}$ as great as with MnO_2. It is thus shown that the efficiency of cupric salt compared with that of manganitic salt under these conditions is somewhere between 0.004 and 0.000001.

6. *The Amount of Chlorine Necessary for the Solution of Gold in the Presence of Manganese Compounds.*

In experiment 15 (*a*), with MnO_2, 0.01640 g. of gold was dissolved in 34 days with solution one-tenth normal with respect to chlorine. A solution with but 40 per cent. as much Cl (experiment 16*b*) dissolved 31 per cent. as much gold in 14 days as was dissolved in the more concentrated solution in 34 days. These results show that in 15 (*a*) conditions are probably approaching equilibrium and also that the solvent power of chlorine is approximately proportional to the amount present. That a weighable quantity of gold is dissolved when only a trace of chlorine is present is shown by experiment 13 (*b*), in which chlorine was introduced without intention.

7. *The Precipitation of Gold.*

Although gold is readily precipitated by organic matter, this reaction is not of great importance in igneous rocks. There ferrous sulphate is the chief precipitating-agent. Ferrous sulphate is formed by the oxidation of pyrite, but in the presence of oxygen and H_2SO_4 it becomes ferric sulphate, which does not precipitate gold. Below the water-table, where pyrite is more abundant and free oxygen less abundant, ferrous sulphate may persist in the mine-waters. Ferrous sulphate is so effective as a precipitant of gold that it is used for that purpose in metallurgical processes. Experiment 19, by W. J. McCaughey, shows that a minute amount of ferrous sulphate greatly decreases the solubility of gold, although it does not precipitate it completely. With excess of ferrous salt practically all of the gold is precipitated. Don[40] has shown that many of the sulphate mine-waters of New Zealand and Australia contain abundant ferrous iron; and that such waters will first precipitate gold, but after oxidation will dissolve it.

Ferrous sulphate is formed in the upper part of a lode above the water-table; but, owing to the open condition of that part of the lode, air is freely admitted and ferric sulphate forms, at the expense of ferrous sulphate and sulphuric acid. This reaction takes place almost instantaneously if MnO_2 is present (experiment 20), for ferrous sulphate and manganese dioxide are under

[40] *Trans.*, xxvii., 599 (1897); p. 175, this volume.

these conditions incompatible. Manganese dioxide then not only releases the solvent for gold, but eliminates the salt which precipitates it. It is doubtful whether appreciable amounts of gold are ever carried far below the water-table in mines where the waters carry ferrous sulphate, but, in the presence of MnO_2, ferrous sulphate may be eliminated below the water-table.

When manganese dioxide takes part in the reactions by which, under the conditions named, gold is dissolved, transported and precipitated, the manganese salt is itself changed. At the surface pyrolusite, MnO_2, forms, for there an excess of oxygen prevails; and this mineral is commonly found in the gossan of manganiferous lodes. When solutions containing H_2SO_4 and NaCl react on MnO_2 there is a tendency to form $MnSO_4$, and some manganese goes into solution as sulphate, but salts of manganese with higher valence may also form. In this connection Dr. R. C. Wells has offered the following statement:

"In an acid solution containing some free chlorine, such as has been assumed to be effective in dissolving gold, there would also be a tendency towards the formation of permanganic acid. On the other hand, the production of the chlorine necessarily results in the reduction of the manganese compound. Now a manganous salt is known to react with permanganate to reproduce MnO_2, and this illustrates the tendency of manganese to pass with ease from one stage of oxidation to another. The precipitation of manganese will occur more and more as the solution loses its acidity. It is well established that manganous salts in an acid environment are very stable; but in neutral or alkaline solutions they oxidize more vigorously, one stage of their oxidation being the manganic salt which hydrolyzes into $Mn_2O_3.H_2O$ (manganite), with even greater ease than ferric salts into limonite.

"In these ways the migration of an acidic solution would result in the transportation of both gold and manganese. But in a region of basic, alkaline and reducing environment the manganese would be re-precipitated, the free acid neutralized, the chlorine absorbed by the bases and removed, and owing to the accumulation of the ferrous or other reducing salts, the gold would be re-precipitated."

V. The Transfer of Gold in Cold Solutions.

1. *Restatement of the Processes as Related to Secondary Enrichment.*

Every theory of secondary enrichment of the metals consists essentially of three parts: (*a*) solution, (*b*) transportation, (*c*) precipitation.

(*a*) As already stated, there is in the upper part of the ore-deposit, where oxidation prevails, abundance of ferric sulphate

and sulphuric acid. A little salt, NaCl, or other chloride, is generally present. The H_2SO_4, reacting upon NaCl, gives HCl, which, in the presence of MnO_2, gives nascent chlorine, which dissolves gold. Some manganese goes into solution as sulphate, but certain higher manganates are probably formed as well.

(*b*) This chemical system will move downward under hydrostatic head. If it comes into a zone containing pyrite it will react upon the pyrite, and in the oxidation of the latter more iron sulphates and acid will be formed. If manganese dioxide is present, or if permanganic acid had been formed, no gold will be precipitated, and the system, with gold still in solution, will move to greater depths before ferrous sulphate can become effective.

(*c*) But as the system moves downward, where no new sources of oxygen are available, the excess of acid is removed. There are many ways by which acidity is reduced along with these reactions, but the principal one is probably the kaolinization of sericite and feldspar. In these reactions sodium, potassium, calcium, magnesium, and other sulphates are formed from acid and silicates; the silica remaining as SiO_2 and kaolin; the alkalies and alkalic earth sulphates going into solution. As the acidity decreases, iron and manganese compounds tend to hydrolyze and deposit oxides. At this stage of oxidation $FeSO_4$ becomes increasingly prominent, and not only completely inhibits further solution of gold but becomes increasingly effective as a precipitant. Thus manganite is probably precipitated with gold. The fractures in the primary pyritic gold-ore below the water-level thus become coated with a manganiferous gold-ore, which may be very rich. The excess of oxygen which the system has carried down is used up in the manner indicated, and in this process limonite is formed, consequently the manganiferous gold-ore deposited in the fissures and cracks contains iron and kaolin as well as manganese oxides.

2. *Association of Gold with Manganese Oxides.*

Oxidized manganiferous ore frequently carries silver[41] without gold. In the oxidized zone such ore should be common;

[41] *Mining and Scientific Press*, vol. xciv., No. 25, p. 796 (June 22, 1907).

but in the sulphide zone different relations, according to the requirement of the theory, should generally be shown. In this zone the manganese acts not so much as a solvent for gold, but rather as an agent which delays precipitation by converting the ferrous sulphate, which precipitates gold, to ferric sulphate. The gold has presumably been dissolved higher up, but it traveled downward in solution in cracks in the primary sulphide ore. It would be expected that the deeper-seated manganiferous ore, unlike the lean ore in the oxidized zone, would be rich in gold. S. F. Emmons informs me that there is a common feeling among the miners in Colorado that manganese is a very good sign of rich ore. The same feeling exists in the minds of many prospectors elsewhere. F. L. Ransome says [42] that in the Camp Bird and Tomboy mines black oxide of manganese occurs in the deeper workings (year 1901), and usually indicates good ore. In these cases, according to Ransome, "The oxide appears to be associated with post-mineral fracturing . . . and to have been deposited later than the bulk of the ore." In general, the gold-deposits near Telluride and Ouray show very little secondary enrichment and the primary ore is rich enough to pay handsomely, but the small rich manganese streaks may be rationally explained by the processes indicated. In the deposition of chalcocite ferrous sulphate is formed, and this would readily precipitate the gold if any were held in the solution. The relation of chalcocitization and deep-seated precipitation of gold is discussed on p. 798.

In the oxidized zone small bunches of very rich manganiferous gold-ore are often found. I have seen such ore above the sulphide zone in certain camps in Nevada. Such bunches of rich ore were probably formed when they were surrounded by sulphides, but were overtaken by the oxidized zone, which moves progressively downward, and the gold in the rich ore has not yet been dissolved. Such ores should in general be more abundant and richer in the lower part of the oxidized zone than near the apex, where they have been exposed for longer periods to the solutions dissolving gold. They may be compared with the rich partly-oxidized chalcocite which appears near the surface in certain copper-mines. Such ore

[42] A Report on the Economic Geology of the Silverton Quadrangle, Colorado, *Bulletin No.* 182, *U. S. Geological Survey*, p. 101 (1901).

remains above the water-level because the table has been depressed more rapidly than the copper sulphide has been dissolved. The mutual relation of these processes is discussed by W. Lindgren in his monograph on the copper-deposits of the Clifton-Morenci district, Arizona.[43]

3. *The Oscillating, Descending, Undulatory Water-Table.*

The terms "water-table" and "level of ground-water" are generally used to describe the upper limit of the zone in which the openings in rocks are filled with water. This upper limit of the zone of saturation is not a plane, but a warped surface. It follows in general the topography of the country, but is less accentuated. It is not so deep below a valley as below a hill, but it rises with the country towards the hill-top and in general is higher there than in the valley. Nor is it stationary. In dry years it is deeper than in wet years, and in dry seasons it is deeper than in wet seasons. The difference of elevation between the top of this zone in a wet year and in a dry year is normally greater under the hill-top than on the slopes and in the valleys. In mines where the ground is open the level of ground-water probably changes with every considerable rain. Consequently, there is a zone above ground-water in dry periods but below it in wet periods, and in hilly countries this may be of considerable vertical extent. Thus the water-table oscillates, though in general moving downward with degradation of the land-surface. It is in this zone of oscillation of the water-table that chemical activity is most varied. Without any change in the character of the drainage or of the more-constant conditions controlling the water-circulation, the chemical composition of the solutions affecting this zone may change from season to season. They may at one time be ferric sulphate or oxidizing waters and at another time ferrous sulphate or reducing waters, since, after a wet season, the ferrous sulphate waters from below would tend to rise, after dilution with fresh water added by the rains. Consequently, the minerals of this zone may include, besides the residual primary and secondary sulphides, the oxides, native metals, chlorides, sulphides, carbonates, etc. Between the top of this zone and the surface or the apex of the deposit chemical activity is probably slow, be-

[43] *Professional Paper No. 43, U. S. Geological Survey*, p. 232 (1905).

cause there is a scarcity of sulphides and other easily-altered minerals to supply the salts upon which the chemical activity of ground-water in a large measure depends. As the country is eroded, this zone also descends; and if a mineral or metal persists long enough, the upper limit of the zone of active change passes below it. The mineral is thus "marooned," and, not being exposed to mineral-laden waters, it may ultimately be exposed at the outcrop of the deposit.

4. *The Several Successive Zones in Depth.*

As is clearly set forth by S. F. Emmons, W. H. Weed, and others, many metalliferous lodes, when followed from the surface down the dip, show characteristic changes. Below the outcrop, the upper part of the oxidized portion of the lode may be poor. Below this there may be rich oxidized ores; still farther down, rich sulphide ores; and below the rich sulphides, ore of relatively low grade. Such ore is commonly assumed to be the primary ore, from which the various kinds of ore above have been derived. The several types of ore have a rude zonal arrangement, the so-called "zones" being, like the water-table, highly undulatory. They are related broadly to the present surface and to the hydrostatic level, but are often much more irregular than either; for they depend in large measure on the local fracturing in the lode which controls the circulation of underground waters. Any zone may be thick at one place and thin, or even absent, at another. If these zones are platted on a longitudinal vertical projection, it is seen that the primary sulphide ore may project upward far into the zone of secondary sulphides, or into the zone of enriched oxides, or into the zone of leached oxides, or may even be exposed at the surface. The zone of secondary sulphide enrichment (which is not everywhere present) may project upward far into the zone of rich oxidized ore, or into the zone of leached oxides, or may outcrop at the surface. The zone of sulphide enrichment nearly always contains considerable primary ore, and very often the secondary ore is merely the primary ore containing in its fractures small seams of rich minerals. The zone of enriched oxides is generally found above the water-table when the latter is at the lowest. The zone often extends to the outcrop. Indeed, it is at such places that most mines are discovered, for in districts

not known to contain metalliferous deposits a lean or barren outcrop is generally not extensively explored by prospectors. In regions of rapid erosion, and especially of rugged topography, the conditions for the exposure of rich oxides, or even rich sulphides or primary ore, are more favorable. In places along the outcrop of a deposit where erosion is rapid the richer oxidized or sulphide ores may be exposed, whereas in other places, protected from erosion, and therefore exposed longer to solution, the same outcrop is frequently leached. It is evident that the amount of metal remaining in the upper part of the oxidized zone and at the outcrop depends upon the ratio between the rate at which the metal is dissolved, and the rate at which the valueless constituents are dissolved and removed. Under certain conditions gold is removed very slowly, and the removal of valueless constituents may effect a concentration at the very apex of the lode; while under other conditions, favorable to the solution of gold, it is removed more rapidly than the valueless constituents (such as silica and iron), and, in consequence, the apex and the upper portion of the zone below it are leached. In a country not subject to erosion it would be supposed that the outcrops of manganiferous lodes would be everywhere leached; but rapid erosion may remove the upper part of the lode before it is completely leached, and, under favorable conditions, placers accumulate from the débris of the apex.

It thus appears that all of these zones except that of the primary ore are, broadly considered, continually descending; so that ore taken from the outcrop may represent what was once primary ore; afterwards, enriched sulphide ore; still later, oxidized enriched sulphide ore; later still, leached oxidized enriched sulphide ore; and finally become the surface-ore. Through more rapid erosion at some particular part of the lode, any one of these zones may be exposed; and hence an outcrop-ore of any character is possible. Consequently, longitudinal assay-plans, showing the changes of value in depth, though highly suggestive, and especially so when gold and silver are shown separately, are supplemented by studies of the paragenesis and by physiographic studies, in order that the approximate rate of erosion of the lode at various places may be known. In the absence of such knowledge, it is gener-

ally impossible to tell the genesis of a particular sample of ore from a mine, although this may sometimes be done. When all the data are assembled, however, greater confidence may be placed in the conclusion, since all the factors in the problem are intimately related.

5. *Criteria for the Recognition of Secondary Enrichment.*

I shall not attempt to review all the criteria for the recognition of secondary enrichment. They involve practically all available data relating to the geology and physiography of the region, as well as the observed characteristics of its ore-deposits. But each group of deposits may be studied with certain general criteria in view. Among these are: (1) the vertical distribution of the richer portions of the lode with respect to the present surface and to the level of ground-water; (2) the mineralogy of the richer and poorer portions of the deposits, and the character and vertical distribution of the component minerals; (3) the paragenesis, or the structural relations shown by the earlier ore and that which has been introduced subsequently.

In applying these principles, it should be remembered that circulation is generally controlled by post-mineral fracturing; that the changes depend upon climate and rapidity of erosion, and are affected by regional changes of climate, etc. Although the mineralogy of the ore is a useful aid, there are many minerals which are precipitated from cold solutions and also from ascending hot solutions, and there are many others, the genesis of which is uncertain. Of the minerals formed in the zone of secondary sulphide enrichment, few, if any, are known positively to form under such conditions only. There are some, however, such as chalcocite and covellite, which nearly everywhere are clearly of secondary origin. Ruby silver is frequently, but not always, secondary. Other minerals, such as chalcopyrite, bornite, argentite, etc., have no definite indicative value unless their occurrence suggests that they are later than the primary ore. Where minerals, known to have formed elsewhere by processes of secondary sulphide-enrichment, are clearly later than primary ore, there is a strong presumption that they were deposited by cold descending waters. If it can be shown, in addition, that they do not extend to the bottom of the mine, but are related to the present topography of the

country, then this presumption may be regarded with considerable confidence as confirmed.

Where paragenetic evidence suggests secondary enrichment, it should be determined whether the later minerals are those commonly formed by secondary processes, for, as shown by Weed and others, certain minerals, such as enargite and rhodochrosite, may be deposited by ascending solutions in openings in older ore-bodies.

With respect to gold, the problem is difficult, because the native metal is the only stable gold-mineral known to be deposited from cold dilute solutions. Consequently, the applicable criteria are limited; and the vertical distribution of the richer ore, though suggestive, is not in itself conclusive. Lindgren and Ransome, in their studies at Cripple Creek, have shown that the richer ore-bodies may have in general a relationship to elevation, where there is little or no evidence of deep-seated secondary enrichment. The maximum deposition by ascending hot waters may be greater at one horizon than at another; and the rich ore, though showing broadly certain variations with depth, is in no way related to the water-table. If, however, it can be shown that rich seams of ore cross the primary ore and do not extend downward as far as the bottom of the primary ore, but are related to the present topography of the country, and if it is known that the associated minerals which fill such openings are those which may be deposited by cold waters, the evidence of their secondary origin is practically conclusive. As already shown, seams of gold with limonite and manganese oxides occur in such relations. Similar ore frequently contains chalcocite and argentite also. Such occurrences could with great confidence be attributed to descending waters; and since it is known that they are commonly related to the present surface, a fair presumption is that they will disappear in depth.

In the practical application of such reasoning to gold-bearing deposits it will sometimes be necessary to discriminate between the oxidized manganiferous gold-ore which has resulted simply from the oxidation of a primary manganiferous ore like one containing rhodochrosite, and that which has been deposited in fractures in the sulphides lower down. In other words, it is desirable to know whether rich manganiferous ore in the upper

part of a mine is residual from a primary ore-body, and therefore will probably prove extensive, or represents the result of concentration under more deeply seated conditions after the manner indicated above. This discrimination may be easy in the sulphide zone, where the fractures with rich manganiferous ore are clearly shown; but in the oxidized zone one must rely upon the shape and distribution of the rich bunches. If they are related to cracks in the mass of the oxidized ore, the inference is warranted, in the absence of other evidence, that they are residual secondary ore, and, being genetically related to the present topographic surface, are limited.

The tellurides and selenides of gold are seldom or never deposited from cold solutions; hence native gold is, as already stated, the only gold-mineral which may be so deposited. But native gold is deposited by primary processes also, and is by far the most abundant gold-mineral so deposited. Consequently, in distinguishing between primary gold and gold deposited by cold solutions, one must rely upon associated minerals. When secondary chalcocite or certain secondary silver-minerals are deposited, the attendant reactions precipitate gold. Consequently, the richer bunches of gold-ore in the oxidized zone, residual from secondary ore formed under the deeper-seated conditions, may carry also considerably more copper and silver than the primary ore. But copper, and (unless cerargyrite is formed) silver also, are more readily leached than gold, even when manganese is present. Hence, the evidence of this character may have been destroyed.

With respect to other minerals associated with the secondary gold-ore, we are not warranted, in the present state of our knowledge, in drawing definite conclusions. From the nature of the reactions, I think it may be possible to show that manganite, $Mn_2O_3.H_2O$, is, under conditions of incomplete oxidation, more often associated with the rich gold in such relations than pyrolusite, MnO_2,; for, as already observed, the lower oxide is more likely to be precipitated than the higher, when secondary gold is deposited under deep-seated conditions. But under oxidizing influences the manganese oxides change their character so readily that this criterion, if it has any value, is probably not applicable to ores in the upper part of the oxidized zone, where they have been exposed to more highly

oxygenated waters for a longer time. I make these suggestions with respect to the character of the manganese oxides associated with the rich ore, not because I think the reactions which precipitate manganese are well enough understood to give a positive paragenetic value to the oxidized manganese-minerals themselves, but in the hope that others will ascertain and report the character of the manganese oxide associated with gold in the deeper zone and in the residual products from that zone. The streak of manganite is reddish brown, sometimes nearly black, whereas the streak of pyrolusite is black or bluish black; but mixtures and pseudomorphs of the minerals occur, and it is sometimes almost impossible to determine which oxide is present.

In some gold-veins [44] the vein-cavities near and even a considerable distance below the oxidized zone are filled with a brown or black mud, which is frequently very rich. It is not safe to assume that the gold in such cavities was carried to its present position in solution and precipitated by ferrous sulphate. The fine pulverulent ore which collects in the cracks is rich in gold, and may have been carried downward in suspension. But such ore will generally show a horizontal stratification, which will seldom be shown by the ore deposited from solution. As suggested above, manganite, rather than pyrolusite, is probably formed when gold is precipitated. Such mud, deposited from suspension, may contain either pyrolusite or manganite or both; but it is rational to assume that the mud formed by precipitation in the deeper zone carries very little pyrolusite, but is mainly manganite.

6. *Lateral Migration of Manganese-Salts from the Country-Rock to the Ore.*

Clarke's analyses [45] show that igneous rocks carry an average of 0.1 per cent. of manganese oxide, and many basic rocks carry from 0.2 to 0.9 per cent. Where basic dikes have cut an ore-body, they doubtless contribute manganese to the waters circulating in the deposit. The ore of the Haile mine, in South Carolina, is cut by basic rocks; and the ore-bodies of the Delamar mine, in Nevada, are crossed by a basic dike. Both

[44] Cripple Creek, *Professional Paper No. 54, U. S. Geological Survey*, p. 199 (1906).

[45] *Bulletin No. 330, U. S. Geological Survey* (1908).

of these deposits show secondary enrichment of gold; and in both the better ore is found along the dikes. In general, however, the manganese from the country-rock cannot safely be assumed to have migrated extensively into the ore-deposit, for many analyses of mine-waters do not show manganese; but where manganiferous rocks are intimately fractured and filled with seams of ore it would be supposed that the reactions requiring manganese could take place.

The experiments of Dr. Eugene C. Sullivan, performed at the request of S. F. Emmons, in the investigation of another problem, have an important bearing here and Mr. Emmons has kindly permitted me to publish them in advance of his own paper. In so doing, I have abridged somewhat the statements of Dr. Sullivan.

A sample of the lower white porphyry from the Thespian mine, Leadville, Colo., was finely ground and treated with carbonic acid and with sulphuric acid; the rock contained 0.8 per cent. of iron and 0.033 per cent. of manganese. The ratio is about 24 to 1.

Carbonic Acid.—20 g. of the porphyry was taken in 40 cc. of water, and carbon dioxide was passed into the mixture for some hours. In 20 cc. of the solution 0.03 mg. of manganese were found and no iron. The results are probably correct for manganese to 0.01 mg. Less than 0.01 mg. of iron would have been detected, if present. To preclude the possibility that the solution of manganese was facilitated by its reduction with metallic iron introduced from the hammer in pounding up the sample, another portion was similarly treated after metallic iron and magnetite had been removed by a hand-magnet. In this case 0.1 mg. of manganese and 0.02 mg. of iron were found in 20 cc. of solution.

Sulphuric Acid.—20 g. of the powdered porphyry stood over night in contact with 40 cc. of one-tenth normal sulphuric acid (0.196 g. of H_2SO_4 in 40 cc.). This has roughly the same molecular concentration as a saturated solution of carbon dioxide. The filtrate, 20 cc., contained 1.05 mg. of iron, all in the ferrous condition, and 1 mg. of manganese. The experiment was repeated under the same conditions, except that contact between the rock-powder and the acid was of but a few minutes' duration; 1.20 mg. of iron, practically all ferrous, and 0.90 mg. of manganese were found in 20 cc. of solution. One-tenth of a milligram is about the limit of accuracy in these cases.

Potassium Sulphate.—Neither iron nor manganese could be detected in the solution after treatment of the rock-powder with potassium sulphate.

Manganese is therefore more readily extracted from the rock than iron under surface-conditions; for, although it is present in the ratio of only 1 : 24 as compared with iron, yet carbonic acid takes out more than three times as much manganese as iron, and sulphuric acid gives a ratio of about 1 : 1.[46]

As to the precipitation of the two metals from a mixture of their salts in solu-

[46] Penrose, The Chemical Relation of Iron and Manganese in Sedimentary Rocks, *Journal of Geology*, vol. i., pp. 356 to 370 (May–June, 1893). Vogt, Bog Manganese-Ores, *Zeitschrift für praktische Geologie*, vol. xiv., p. 217 (July, 1906).

tion, the following experiment shows that ferrous compounds are more readily oxidized and precipitated than manganous compounds. Ferrous sulphate solution and manganous sulphate solution were mixed in equi-molecular quantities (50 cc. containing 2 mg.-molecules of each *i. e.*, 0.112 g. of iron and 0.110 g. of manganese), with sufficient powdered calcite (Iceland spar) to react with one of the metals (0.200 g.-molecule of calcite). During four weeks the mixture, in a roomy flask, was occasionally shaken, the stopper at the same time being removed for a moment to allow free access of air. At the end of that time all but 1.5 mg. of the iron had been precipitated, while the manganese was in solution in practically the same quantity as originally. Calcite, however, when in contact with manganous salts alone, in the presence of air, will precipitate the manganese as a higher oxide or hydroxide, especially at elevated temperature.

It thus appears that some manganese is probably contributed to the ore-deposits from the country-rock. I believe, however, that said additions are small, except where space-relations of ore and country-rock are peculiarly favorable. In the upper parts of a vein the circulation is in general downward, and is controlled very closely by fractures, which are more abundant in the upper zone, where the rocks are in general more extensively shattered. Gouge-seams on the walls would also limit the circulation, and tend to keep the vein free from waters of the country-rock. Where calcite or other carbonates are present to precipitate the small amount of manganese in the solutions, one would suppose that the opportunities for slight additions would be increased. Manganese carbonate is less soluble than calcite, and the latter could, under favorable conditions, be replaced by manganese compounds. One part of calcium carbonate is soluble in 1,428 parts of water saturated with carbon dioxide, while one part of manganese carbonate is soluble in 2,000 parts of water so saturated.[47]

In my own experience I have found only trivial stains of manganese in those lodes where it was not present in the gangue of the primary ore; and, in view of its wide distribution in igneous rocks, I believe that the lateral migration of manganese into the ore under the conditions which generally prevail is very subordinate. Though the amount so contributed may facilitate the solution of gold, it is probably inadequate to form sufficient higher manganates or similar salts to suppress effectively the action of ferrous sulphate. Under such conditions the gold could not travel to the reducing-zone below the water-level, but would be precipitated practically at the place where it had been dissolved.

[47] *Lassaigne, in Comey's Dictionary of Solubilities* (1896).

7. *Concentration in the Oxidized Zone.*

The concentration of gold in the oxidized zone near the surface, where the waters remove the valueless elements more rapidly than gold, is fully treated by T. A. Rickard in his paper on the Bonanzas in Gold-Veins.[48] Undoubtedly this is an important process in lodes which do not contain manganese, or in manganiferous lodes in areas where the waters do not contain appreciable chlorine. In the oxidized zone it is sometimes difficult to distinguish the ore which has been enriched by this process from ore which has been enriched lower down by the solution and precipitation of gold, and which, as a result of erosion, is now nearer the surface. It cannot be denied that fine gold migrates downward in suspension; but in all probability this process does not operate to an important extent in the deeper part of the oxidized zone. If the enrichment in gold is due simply to the removal of other constituents, it is important to consider the volume- and mass-relations before and after enrichment, and to compare them with the present values. In some cases, it can be shown that the enriched ore occupies in the lode about the same space as was occupied before oxidation. Let it be supposed that a pyritic gold-ore has been altered to a limonite gold-ore, and that gold has neither been removed nor added. Limonite (sp. gr. from 3.6 to 4), if it is pseudomorphic after pyrite (sp. gr. from 4.95 to 5.10) and if not more cellular, weighs about 75 per cent. as much as the pyrite. In those specimens which I have broken, cellular spaces occupy in general about 10 per cent. of the volume of the pseudomorph. With no gold added, the ore should not be more than twice as rich as the primary ore, even if a large factor is introduced to allow for SiO_2 removed and for such cellular spaces.

Rich bunches of ore are much more common in the oxidized zone than in the primary sulphides of such lodes. They are present in some lodes which carry little or no manganese in the gangue, and which below the water-level show no deposition of gold by descending solutions. Some of them are doubtless residual pockets of rich ore which were richer than the main ore-body when deposited as sulphides, but others are very

[48] *Trans.*, xxxi., 198 to 220 (1901).

probably ores to which gold has been added in the process of oxidation near the water-table by the solution and precipitation of gold in the presence of the small amount of manganese contributed by the country-rock. In view of the relations shown by the chemical experiments it is probable that very little manganese will accomplish the solution of gold, but, as already stated, it requires considerably more manganese to form appreciable amounts of the higher manganese-compounds which delay the deposition of gold, suppressing its precipitation by ferrous sulphate. In the absence of larger amounts of the higher manganese-compounds, the gold would probably be precipitated almost as soon as the solutions encountered the zone where any considerable amount of pyrite was exposed in the partly-oxidized ore; for Buehler and Gottschalk have lately shown that oxygenated solutions attack pyrite and dissolve it in a comparatively short time, and McCaughey has shown that even traces of the ferrous sulphate thus formed precipitate gold almost immediately. From this it follows that deposits showing only traces of manganese, presumably supplied from the country-rock, are not enriched far below the zone of oxidation.

8. *Vertical Relation of Deep-Seated Enrichment of Gold to Chalcocitization.*

In several of the great copper-districts of the West (see group 3, p. 806) gold is a by-product of considerable value. In another group of deposits, mainly of Tertiary age (see group 4, p. 807), and younger than the copper-deposits, silver and gold are the principal metals, and copper, when present, is only a by-product. But in some of these precious-metal ores chalcocite is, nevertheless, the most abundant metallic mineral, often constituting 2 or 3 per cent. of the vein-matter. Frequently it forms a coating over pyrite or other minerals. Some of this ore, appearing in general not far below the water-table, is fractured, spongy quartz, coated with pulverized chalcocite. It frequently contains good values in silver, and more gold than the oxidized ore or the deep-seated sulphide ore. Clearly, the conditions which favor chalcocitization are favorable also to the precipitation of silver and gold.

The exact chemical reaction which yields chalcocite is not

known. At 100° C., according to Dr. H. N. Stokes,[49] the reaction with pyrite is probably about as follows:

$$5\,FeS_2 + 14\,CuSO_4 + 12\,H_2O = 7\,Cu_2S + 5\,FeSO_4 + 12\,H_2SO_4.$$

In the cold, the reaction may differ in details, but without doubt much ferrous and acid sulphate is set free. Attendant reactions confirm this statement; for, if calcite is present, gypsum is formed by the reaction of H_2SO_4 on lime carbonate; and, if the wall-rocks are sericitic, kaolin is formed by the acid reacting upon potassium-aluminum silicate, the potash going into solution as sulphate. The abundant ferrous sulphate must quickly drive the gold from solution, and it apparently follows that there may be no appreciable enrichment of gold below the zone where chalcocitization is the prevailing process. In deposits such as those of disseminated chalcocite in porphyry, where the chalcocite occurs in flat-lying zones related to the present surface, and where the ore from which chalcocite was derived carried gold, and suitable solvents were provided, there should be a comparatively even distribution of gold, which should increase and decrease with the chalcocite of the secondary ore. A different ratio of values should be found in the oxidized low-grade capping above the chalcocite, for the solution of gold, even under the most favorable conditions, appears to lag behind the solution of copper, and this should be more marked in these deposits, since in all available analyses the porphyries are low in manganese, and rhodochrosite is not noted in the primary ore. I am informed that a fairly-constant ratio between copper and gold is very noticeable in the disseminated deposits at Ely and at Bingham. That whatever gold is present in the rock below chalcocitized pyrite is not a result of deposition from cold solution, is reasonably certain under the conditions named.

9. *Vertical Relations of Silver-Gold and Gold-Silver Ore in Deposits Carrying Both Metals.*

This paper will not discuss in detail the processes of secondary enrichment of silver-deposits—a subject already treated in

[49] Unpublished MSS. quoted by Lindgren in *Professional Paper No.* 43, *U. S. Geological Survey*, p. 183 (1905), and in Weed's translation of Beck's text-book.

our *Transactions* by S. F. Emmons, W. H. Weed, and C. R. Van Hise. There are, however, certain deposits mainly associated with Tertiary rocks, in which both silver- and gold-values are important. Examples are the Comstock lode, Tonopah, Tuscarora, etc. Where physical conditions are favorable, deposits of this type should show in general a concentration of gold at certain horizons, and of silver at other horizons, depending upon the composition of the mine-waters and other factors. The determination, in such mines, of the principles controlling the mutual relations, especially in the deeper zones of the gold-silver and the silver-gold ore-bodies, would have great practical value. So far as I know, no record of experiments with solutions containing both sulphates and chlorides and a mixture of gold and silver is available. The solubilities of silver-salts lately determined by Kohlrausch (quoted by Alexander Smith) are suggestive. He found that at 18° C. a saturated aqueous solution of $AgSO_4$ contains 5.5 g. per liter; but at this temperature water holds in solution only 0.0016 g. of silver chloride per liter. That silver is held in solution by mine-waters carrying sulphates and chlorides was shown by J. A. Reid.[50] Such waters in a Comstock mine carried about 188 mg. of silver and 4.15 mg. of gold in a ton of solution.

The effect, on a manganiferous silver-ore, of a solution carrying chlorides would be to liberate chlorine, which would react with silver to form "horn-silver." This would be fixed in the manganiferous ore, and such a silver-ore would be comparatively stable. The oxidized manganiferous silver-ore at Leadville, Colo.,[51] and at Neihart, Mont., in which silver is generally supposed to be carried largely as chloride, may have originated in this manner. On the other hand, rich ores could hardly be formed where the solutions carried abundant sulphuric acid and little or no chlorine, for the soluble silver sulphate would be formed, and the manganiferous ore leached. To determine the genesis of such manganiferous ore, it is desirable to know the silver-content of the primary rhodochrosite, for, as indicated above, two interpretations of the phenomenon are otherwise possible.

[50] *Bulletin of the Department of Geology, University of California*, vol. iv., No. 10, p. 193 (1904–06).

[51] S. F. Emmons, *Monograph No. XII., U. S. Geological Survey*, p. 562 (1886).

As pointed out by Penrose,[52] silver chlorides are formed extensively in arid countries, at or very near the surface. Frequently the workable ore gives out a few feet down. At many places in Nevada, the so-called "chloriders" stripped the surface over considerable areas; but where the unoxidized ore was encountered the mines were abandoned. At some of these places the chloride ore carried little, if any, more gold than the unoxidized, unprofitable silver-gold ore below. The primary ore of many of these deposits carries relatively little pyrite; and the inspection of a number of them gives the impression that the siliceous ores are more favorable than the more highly pyritic ores to the formation of a surface chloride zone. Manganese oxides are not necessary for the formation of the chloride zone. In many of them manganese is absent. If it is present in appreciable amount, if the physical conditions for a downward circulation in the lode are favorable, and if the primary ore carries gold, it would be reasonable to expect an enrichment of gold below the zone of the chloride-enrichment of silver. In the presence of strong acid sulphate waters, silver, like gold, is dissolved from the outcrop; and in some mines, where both metals are present in important quantities, the outcrop and the oxidized zone for a short distance below are leached of both silver and gold.

The migration of both metals with selective solution and precipitation is suggested by the relation of silver-gold and gold-silver ore-bodies on the Comstock lode. The Comstock lode, which has produced more than $200,000,000 silver and $150,000,000 gold, is a broad fault-zone in late Tertiary rocks. The ore-shoots occur here and there in this zone, which is developed more than 4,000 ft. below the surface.[53] Since the deposits were formed there has been extensive fracturing. In the lode there are great bodies of "sugar" quartz which are due, according to Becker,[54] to this movement. Over considerable spaces one cannot obtain fragments of rock as large as one's fist

[52] *Journal of Geology*, vol. ii., No. 3, p. 314 (Apr.–May, 1894).

[53] Clarence King, *Geological Exploration of the 40th Parallel*, vol. iii., *Mining Industry* (1870); John A. Church, *The Comstock Lode* (1879); G. F. Becker, *Monograph No. III., U. S. Geological Survey* (1882); J. A. Reid, *Bulletin of the Department of Geology, University of California*, vol. iv., No. 10, pp. 177 to 199 (1904–06).

[54] *Op. cit.*, p. 272.

which do not show fissures. There were clearly two periods of movement, one before the deposition of the primary ore and one following it. The latter movement, mainly parallel to the lode, gave conditions for an active circulation of water after the primary deposition. According to Dr. Becker, "it is possible that the seams of rich ore in the great bonanza represent a deposition posterior to the final cessation of movement," and "it is also by no means impossible that some of the richer ores have been redeposited, forming at the expense of surrounding bodies of lower grade."[55] As already remarked, analysis of the vadose water of the Comstock shows that it contains both gold and silver. It is noteworthy that this water contains much manganese, presumably as sulphate. Some associated placers were developed, but they are of very subordinate value compared with that of the lode. Oxidation extended downward as far as 500 ft. According to Clarence King,[56] "a zone of manganese oxide occupies the entire length of the lode from the outcrop 200 ft. down." The upper part of this manganiferous zone was probably not of high grade in general, especially in the uppermost portions. I infer that the outcrop and the ore immediately below were in general not so rich as the ore lower down. The longitudinal projections[57] show that many of the stopes carried from below stop some distance below the surface.

Von Richthofen (quoted by Becker) says that "the proportion of gold to silver decreased during the early period of working the lode, but is now (1865) on the increase again." Presumably, silver at the very surface was leached more rapidly than gold. The vadose waters, as shown by Reid,[58] are rich in ferric sulphate; and his analyses, as well as others, show the presence of chlorides in appreciable amounts. The conditions appear to have been favorable for the solution of both silver and gold in the upper levels, even in the comparatively short geological period which has elapsed since the primary ores were deposited. The bonanza ore below consisted largely of stephanite, polybasite, argenite, and other dark, rich

[55] *Monograph No. III., U. S. Geological Survey*, p. 273 (1882).

[56] *Geological Exploration of the 40th Parallel*, vol. iii., *Mining Industry*, p. 75 (1870).

[57] Becker, *op. cit.*

[58] *Bulletin of the Department of Geology, University of California*, vol. iv., No. 10, pp. 177 to 199 (1904–06).

silver-minerals, and in places, according to Dr. Becker, appeared to fill fractures which involved the primary ore. It is well known that this rich ore was more abundant in the upper than in the lower levels. When I visited the district in 1907 I was informed by the foreman at the Consolidated Virginia that large bodies of the hydrothermally-altered porphyry on the Sutro level and below, which contained considerable pyrite, etc., carried also considerable gold and silver, although below the limit of profitable mining. Very few of the ore-bodies which had been worked at those levels were then accessible. The deposits in the upper levels yielded, according to Richthofen, from $70 to $107 a ton, whereas in later years the average value of the ore was not more than $37.

It thus appears that the evidence of the Comstock lode, from the surface down, is favorable to the hypothesis that extensive solution and deposition of gold and silver has taken place, while it is insufficient to show to what extent the great bonanzas owed their values to such processes. In ores formed so near the surface, there is always the possibility that ascending hot waters deposited the maximum portion of their gold and silver at the horizon where they encountered cold oxygenated solutions. Sulphate may form, in such mixtures, and ferrous sulphate tends to drive both gold and silver out of solution. The proportion of gold to silver was presumably higher in the upper part and in the lower part of the lode than in the middle portion. When Richthofen made his report, he estimated that the lode had produced, to the close of 1865, $15,250,000 of gold and $32,750,000 of silver (gold equals 47 per cent. of the silver); whereas Becker reports the amount recovered from 1865 to 1881 as $87,121,988 of gold and $105,548,157 of silver (gold equals 83 per cent. of the silver). If much of the change is due to reworking by descending waters, the greater gold-values in the upper portions of the bonanzas indicate that gold was dissolved less readily than silver, and silver precipitated less readily than gold, in the sulphate-rich water of this mine.

The relation of "horn-silver" to the surface is different from hat shown in the "chloride mines" mentioned above. According to Clarence King,[59] silver chloride is accidental, although

[59] *Op. cit.*, p. 82.

rare small crystals were found at the outcrop in the Gold Hill group. It occurred, however, at the 900-ft. level of the Yellow Jacket, where, judging from the descriptions, it was present in considerable amount.

Ferrous sulphate precipitates both silver and gold in acid solutions. The precipitation of gold is, however, many times more rapid and more effective than that of silver. Where silver chloride is not precipitated, one would suppose that cold solutions would transfer the silver to greater depths than gold. Since silver chlorides are not abundant (King), this, if no other, is an argument for the hypothesis that the lower-grade gold-silver ores ($37 a ton or less, Becker [60]), which were worked in the levels below the great silver-gold bonanzas, were in the main primary. These ore-bodies were not accessible to me when I visited the Comstock mines, and the speculation is not based on paragenetic evidence.

The relations of silver-gold to gold-silver ores in the Exposed Treasure mine, near Mojave, differ from those at the Comstock. In the surface-zone, horn-silver has been formed in considerable amount. The proportion of gold to silver in this zone is 1 : 72 (weight). In the lower friable siliceous ores, the proportion of gold to silver is 1 : 12; and in the sulphide ores below the water-table, where the gold-content had increased 150 per cent. above the average in the friable siliceous ores, the proportion of gold to silver was as 1 to 2.[61] The Exposed Treasure ores are, like those of the Comstock, manganiferous.

It thus appears that there are two types of enrichment in deposits of manganiferous gold- and silver-ores. In one of them silver chloride is concentrated in the manganiferous oxidized ores of the upper levels, and gold is concentrated below. In the other, silver chloride is subordinate, while both gold and silver are concentrated below the oxidized zone. Possibly the difference could be explained if the amount of chlorine were determined in the waters of deposits of both types. Silver chloride is soluble in an excess of alkaline chlorides. Those deposits in which horn-silver is not present may have been leached by waters unusually rich in chlorides.

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[60] *Monograph No. III., U. S. Geological Survey*, p. 18 *et seq.* (1882).

[61] Courtenay DeKalb, *Trans.*, xxxviii., 319 (1907).

VI. Review of Mining-Districts.

The purpose of this inquiry is to ascertain whether the ore-deposits of the United States give evidence that gold is more readily transferred in manganiferous deposits than in deposits which do not contain manganese, a hypothesis suggested by the chemistry of the processes of solution and precipitation.

1. If gold is more readily dissolved in manganiferous deposits, it would be supposed that placers form less readily from pyritic manganiferous lodes than from lodes containing no manganese. If, in areas where the waters carry appreciable chlorine, placers have formed as extensively from such lodes as from lodes free from manganese, then the hypothesis fails.

2. The manganiferous lodes, in areas of chloride waters, as in the undrained areas of the Great Basin, should in general show less gold at the outcrop and in the upper portion of the oxidized zone than below. In silver-gold deposits, however, silver, on account of the insolubility of the chloride, may remain, or be concentrated, in the oxidized manganiferous zone. Bunches of rich gold-ore carrying oxidized manganese in the oxidized zone are not necessarily fatal to the theory; for, as already stated, these are probably residual from the zone of secondary enrichment. An extensive enrichment in gold of the oxidized manganiferous ores at the surface, which are shown not to be residual from the zone of secondary ores, would indicate that the selective processes lack quantitative value, if the waters carry chlorine, and if the primary ores, from which the manganiferous oxidized ores are derived, carry appreciable pyrite to supply sulphate.

3. If in certain lodes gold migrates below the water-table, it should be precipitated quickly by ferrous sulphate. But MnO_2 converts ferrous sulphate to ferric sulphate, which does not precipitate gold. Hence, MnO_2 favors the solution of gold, and converting the ferrous salt to ferric sulphate removes the precipitant. Consequently, if auriferous lodes show enrichment in the deeper zone but related to the present surface of the country, manganiferous lodes should, the other favorable conditions provided, show greater differences in values with respect to gold than lodes free from manganese.

Gold-Provinces of the United States.

As Lindgren[62] pointed out in 1902, the principal gold-deposits of the United States may be divided into four groups. The deposits of each group belong mainly to one metallogenetic epoch, and certain relationships are clearly shown. This classification, which has thrown much light on the genesis of the deposits, is useful as an instrument for study and for comparison of the deposits with respect to the problem of the migration of gold in them.

1. The Appalachian gold-deposits, and those of the Homestake type in South Dakota, are the most important representatives of the oldest group. These deposits generally yield placers, are usually low grade below the water-level and are singularly free from bonanzas. They are, in general, not greatly leached near the surface, and may have been enriched by the removal of other material more rapidly than gold. At only one of them, the Haile mine, in South Carolina, it is thought probable that gold has been carried below the water-level. The Homestake mines show little evidence of secondary enrichment by transfer of gold, as will appear in the review that follows. Judging from descriptions, practically all of these deposits are free from manganese.

2. The California gold-veins and related deposits in Nevada (Silver Peak) and in Alaska (Treadwell, etc.) are younger than the Appalachian deposits, and were probably formed in the main in early Cretaceous times. These deposits, where physiographic conditions are favorable, have generally yielded rich placers. At many places, moreover, the ore is worked at the very surface, and, as will appear in the subsequent review, there is very little evidence of the migration of gold to the deeper zones. In the places where detailed work has been done, rhodochrosite is never a gangue-mineral, although manganese oxide does occur in traces in the country-rock, and rhodochrosite is found in a few places in veinlets in the mining-districts but not associated with the gold-veins.

3. The deposits of the third group are later than the early Cretaceous, and some of them are probably early Tertiary.

[62] The Gold Production of North America, *Trans.*, xxxiii., 790 to 845 (1902); p. 424, this volume. Metallogenetic Epochs, *Economic Geology*, vol. iv., No. 5, pp. 409 to 420 (Aug., 1909).

They are extensively developed in Montana, Nevada, Utah, and Colorado. Mr. Lindgren calls this group the Central Belt. Many of its deposits have yielded considerable gold, and in certain other districts very closely related genetically (Butte, Georgetown silver-gold lodes, Cortez Nevada, Tintic, etc.) much gold has been obtained as a by-product to copper- or silver-mining. Some of these deposits have yielded placers and some have not. At Philipsburg and Neihart, Mont., Georgetown, Colo., and elsewhere, the deposits show a secondary enrichment of silver below the water-table. At Philipsburg, and probably at some other places, an enrichment in gold accompanies this concentration of silver. Some of the lodes of group 3 carry much manganese, and some carry none. Present data are meager for most of these districts. The determination of gold from the surface down in a large number of deposits would serve as a useful check to the conclusions based upon the chemistry of the processes involved in its solution and precipitation.

4. Group 4 includes the most recent ore-deposits in the United States. All of them are Tertiary, and most of them are Miocene or Pliocene. In general, they were formed relatively near the surface, and in some places it is highly probable that not more than a thousand feet of vein-material has been removed by erosion since the ores were deposited. The majority of these deposits carry silver, and in many of them its value is greater than that of the gold; but they have supplied, notwithstanding, about 25 per cent. of the gold-production of North America. They are typically developed in Nevada (Comstock, Tonopah, Goldfield, Tuscarora, Gold Circle); California (Bodie); Idaho (De Lamar); South Dakota (later than Homestake type); Colorado (Cripple Creek, Idaho Springs, Rosita Hills, San Juan, etc.); Montana (Little Rockies, Kendall, etc.). Many occurrences in Mexico should probably be placed here, and likewise those of the Aleutian Islands, described by Becker. The deposits of this group have not supplied much placer-gold. They have not been exposed to erosion so long as the older deposits. In general, the gold is finely divided. It may have been scattered or it may have been redissolved and deposited lower down. Many of these deposits are in arid countries, where conditions for working placers are not favorable; but,

even those in well-watered districts supply relatively little placer-gold. Manganese is abundant in some of these deposits (Comstock, Exposed Treasure, Tonopah); it is very sparingly present in others (Little Rockies); in still others (Goldfield) it is almost entirely absent.

A few small placers are associated with the manganiferous lodes, although at some places, as at Tuscarora, Nev., they seem to have been derived from veins near-by which are not manganiferous, as is probably the case with some deposits of group 3 (Butte, Philipsburg). Many of the California veins (group 2) carry rich ore at the very surface, but the Tertiary gold-veins are generally richer in gold a few feet below the surface than at the outcrop. Doubtless, many of them would have been overlooked if it had not been for the concentration of horn-silver and argentiferous pyromorphite at the surface. At many of these deposits, however, good gold-ore is found only a few feet below the surface.

It thus appears that practically all of the manganiferous gold-deposits of the United States, so far as they have been described, may be included in groups 3 and 4; that nearly all described deposits where relations indicate a migration of gold belong to the same groups; that placers are much less abundantly developed than in groups 1 and 2; and that outcrops less frequently supply gold; that secondary enrichment below the water-table, if carried on at all, proceeds with extreme slowness in groups 1 and 2, but may be more pronounced in deposits of groups 3 and 4. Not all of these deposits carry manganese, however, and those which do not carry it should be expected to show relationships more nearly approximating those of groups 1 and 2.

5. Some deposits formed at hot springs carry gold. As a rule, traces only are found in the sinters, and at many places even traces are not detected. This is readily explained when it is noted that these springs frequently carry both sulphates and iron. If the sulphates are due to contamination with oxygenated surface-waters, then such waters, before complete oxidation, would precipitate gold. Since only a little ferrous sulphate precipitates practically all of the gold in a solution, it would be supposed that the major deposition would be some distance below the surface, where oxygen-bearing waters first

contaminated the hot solutions, and not at the surface. The same argument should apply to silver also, although the action of the ferrous salt on solutions carrying silver is not nearly so rapid as on solutions carrying gold. In the hot solutions, manganese, even if it were present, would probably not hold the gold or silver in solution by oxidizing ferrous salts, for ascending hot waters deposit manganous rather than manganitic compounds.

1. *Southern Appalachian Districts.*—The gold-deposits of the southern Appalachians are among the oldest gold-deposits of the United States, and were probably formed,[63] in the main, 3 or 4 miles below the surface at the time of deposition. Many of them are in mica-schist and other crystalline rocks, and some are closely associated with granitic intrusions. Some are cut by diabasic intrusives, presumably later than the ore. The deposits have yielded considerable placer- and lode-gold. The minerals, according to Graton,[64] include quartz, sericite, biotite, fluorite, gold, pyrite, galena, blende, pyrrhotite, chalcopyrite, magnetite, etc. Manganese-minerals are not mentioned. In Becker's tabulation of the minerals of the gold-mines of the southern Appalachians, compiled from all previous descriptions and including mines not described by Graton, pyrolusite is mentioned in only three mines and rhodochrosite in one.[65]

Few of these deposits have been extensively explored in depth, and consequently data respecting the vertical distribution of the gold-values are meager. Many of them are profitable near the surface, partly by reason of the rotten condition of the rock, which renders it more easily worked, and partly because gold is accumulated or enriched by the removal of valueless material. In general there is, according to Graton, very little evidence for or against the theory of the migration of gold; but such migration, if it has taken place, has been extremely slow, for areas which have probably been exposed since Tertiary time show a marked concentration at and near the surface. Possibly some gold has been transferred to lower

[63] Lindgren, *Bulletin No.* 293, *U. S. Geological Survey*, p. 124 (1906).

[64] *Idem*, p. 62.

[65] *Sixteenth Annual Report, U. S. Geological Survey*, Part III., *Mineral Resources of the U. S.*, p. 277 (1894–95).

levels at the Haile mine, South Carolina,[66] where the limit of profitable mining is in general less than 200 ft. below the limit of complete oxidation. In this zone scales of pyrite and free gold are found in joint-cracks, indicating a comparatively recent age. The deposits are cut by basic dikes. Prior to Graton's work, many thought that the primary deposition of gold was genetically related to the dikes,[67] since the workable ore appears to be limited to the area cut by them. If the basic dikes (like most basic rocks) carry manganese, then our hypothesis supports, and is supported by, Graton's opinion that secondary enrichment has probably taken place, and the conflicting views of Graton and Maclaren respecting the genesis of the ores are thus reconciled.

Certain ore-deposits of Alabama recently described by H. D. McCaskey[68] comprise fissure-veins in granite and lenticular bodies in schists. The principal minerals are quartz, pyrite, and gold. Some garnet is found in the vein-quartz at Pinetuckey. Weathering extends to water-level (from 40 to 80 ft. below the surface). The ores are oxidized above this level and are generally free-milling, but below this level the ore is not profitably amalgamated so far as explored in depth. The ores are fairly regular in width and values, and no evidences of enrichment below the water-level are recorded.

2. *Black Hills, S. D.*—The principal gold-deposits of the Black Hills[69] are in pre-Cambrian schists which, like the ore-bodies, are cut by Tertiary intrusives. Since the Cambrian conglomerates contain placer-gold,[70] some of the ores must have been deposited in pre-Cambrian times. The most important deposits are comprised in the Homestake belt, about 3 miles long and 2,000 ft. wide. The principal minerals are quartz, dolomite, calcite, pyrite, arsenopyrite, and gold, with which are associated the minerals of the schist: quartz, orthoclase, hornblende, biotite, garnet, tremolite, actinolite, titanite, and graphite.[71] The ores, though uniformly of low grade, are

[66] Graton, *Bulletin No.* 293, *U. S. Geological Survey*, p. 67 (1906).

[67] Maclaren, *Gold*, pp. 57, 592 (1908).

[68] *Bulletin No.* 340, *U. S. Geological Survey*, p. 36 (1908).

[69] Irving, Emmons, and Jaggar, *Professional Paper No.* 26, *U. S. Geological Survey* (1904).

[70] W. B. Devereux, *Trans.*, x., 469 (1881–82).

[71] J. D. Irving, *loc. cit.*, p. 90.

very profitable. Some of the ores at the surface were below the average tenor, while other surface-ores were two or three times as rich as the average. The values extend downward as far as exploration has gone, and are fairly uniform to 1,000 ft. or more below the surface. In general, according to S. F. Emmons, secondary enrichment by surface-leaching has had relatively small importance.[72]

3. *Treadwell Mines, Alaska.*—At the Treadwell mines, Douglas Island, Alaska, large dikes of albite-diorite intrude greenstones and schist, and the shattered diorite has been extensively replaced by mineralizing solutions, and cemented by low-grade gold-ore. The minerals include quartz, albite, rutile, chlorite, epidote, calcite, siderite, pyrite, pyrrhotite, magnetite, chalcopyrite, and molybdenite. Manganese-minerals are not reported.

The mines have been developed 2,000 ft. down the dip. According to A. C. Spencer,[73] the ore shows no progressive change in appearance or values with increasing depth. In the lowest level it is quite as rich as in the upper workings; and it is evident that changes on the dip are no greater than along the strike. Nothing in the character of the ore indicates any important concentration of values by oxidizing waters. The fact that extensive placers were not formed is not opposed to the view expressed by Spencer that the gold has not been transferred; the country has been recently glaciated, and surface-accumulations have been scattered. The gold accumulated at the apex since glacial time was, indeed, recovered by sluicing.

4. *Berner's Bay, Alaska.*—According to Adolph Knopf, the lodes of the Berner's Bay district are fissure-veins in diorite. There is no evidence of secondary enrichment of gold or of leaching near the surface. The deposits contain no manganese.

5. *The Mother Lode District, Cal.*—The Mother Lode district, as described by F. L. Ransome,[74] is an area of crystalline schists and altered igneous rocks with intruded granodiorite and related rocks. The deposits are fissure-veins, which generally trend northwestward, and, at many places, parallel the schistosity of the country-rock. The ore does not contain

[72] *Professional Paper No.* 26, *U. S. Geological Survey*, p. 79 (1904).
[73] *Bulletin No.* 287, *U. S. Geological Survey*, pp. 32 and 115 (1906).
[74] Mother Lode District, *Folio No.* 63, *U. S. Geological Survey*, p. 3.

manganese-minerals. Placers are abundantly developed, and at many places rich ore is found at the very surface. According to Ransome, there is no evidence that the mines grow suddenly richer at any arbitrary depth, nor is there any recognizable regular change in the value of pay-shoots with depth, below the zone of superficial weathering. Some of these deposits are very regular and uniform in values, and have been developed to very great depth.

6. *Nevada City and Grass Valley, Cal.*—The area of Nevada City and Grass Valley [75] includes metamorphosed Carboniferous sedimentary rocks, compressed into isoclines, and associated igneous rocks less intensely metamorphosed. Above these are slates with associated diabase and serpentine. These rocks are folded and metamorphosed, but are not so intensely compressed as the Carboniferous. Intruded into these rocks are great bodies of granodiorite, probably of early Cretaceous age. The ore-deposits are strong fissure-veins, formed after the granodiorite intrusions. The minerals are quartz, chalcedony, magnetite, sericite, mariposite, pyrite, pyrrhotite, chalcopyrite, galena, blende, scheelite, arsenopyrite, tetrahedrite, stephanite, and cinnabar. Some earthy manganese-ore occurs in small fissures in the granodiorite, but not in connection with the quartz veins.

Near the surface [76] the upper part of a vein is generally decomposed, forming a mass of limonite and quartz. The decomposition seldom extends more than 200 ft. on the incline of a vein dipping 45°, or more than 150 ft. below the surface. Fresh ore is sometimes found almost at the surface. The surface-ore is generally richer than the fresh ore below, owing to the liberation of gold from the sulphides and the removal of substances other than gold. In this process, silver is also partly removed. In some of the mines, the lodes have been followed down the dip for 2,000 or even 3,000 ft. The unoxidized ore shows no gradual diminution of tenor in the pay-shoots below the zone of surface-decomposition. "Within the same shoot there may be many and great variations of the tenor, but there is certainly no gradual decrease of it from the

[75] Waldemar Lindgren, *Seventeenth Annual Report, U. S. Geological Survey*, Part II. (1895–96).

[76] *Loc. cit.*, p. 128.

surface down."[77] Important placer-deposits were formed from these veins.

7. *The Ophir District, Cal.*—The rocks of the Ophir district[78] comprise amphibolite-schists and massive amphibolites, with intrusions of granodiorite. These rocks are cut by quartz veins which fill co-ordinate fissures. The minerals are gold, electrum, some iron, copper and arsenical pyrites, with galena, blende, tetrahedrite, and molybdenite. The gangue is mainly quartz with a little calcite. The proportion of gold to silver varies by weight from 1:1 to 1:10, the values of gold predominating. Certain small ore-shoots, in veins in the amphibolite, carry more than the usual tenor of gold; and the richest shoots are usually found where veins cross the belts rich in iron. According to Lindgren, such ore-bodies may have been enriched by leaching. The common statement, that the gold-vein becomes barren as the depth from the surface increases, is not justified, in his opinion,[79] by the evidence afforded in the mines. The extensive development of placers, the value of the ore near the surface, and the occurrence of valuable ore-shoots just below the surface, are opposed to the notion of extensive migration of gold in these deposits.

8. *Silver Peak, Nev.*—According to J. E. Spurr,[80] the deposits of Silver Peak, Nev., are lenticular masses and fissure-veins in Palæozoic sedimentary rocks. Genetically, they are related very closely to granitic rocks, which, as shown by Mr. Spurr, have alaskitic or pegmatitic phases. They are probably post-Jurassic, and should be grouped with the California gold-veins, with which geologically they have much in common. Of the Drinkwater and Crowning Glory deposits, which are the most important examples, Spurr says that no decided enrichment of the ores by oxidation can be established. The ores in the upper tunnel seem to have been locally richer than any found in the lower tunnel; but this difference has no evident relation with the surface, and is probably original. The values are finely disseminated gold and auriferous sulphides,

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[77] *Op. cit.*, p. 163.

[78] Waldemar Lindgren, *Fourteenth Annual Report, U. S. Geological Survey*, Part II., p. 252 (1892-93.

[79] *Idem*, p. 279.

[80] *Professional Paper No.* 55, *U. S. Geological Survey* (1906).

scattered through vitreous quartz. The character of the ore affords no ground for supposing any great concentration by surface-waters, since the minerals are not easily reached by percolating waters. No ore-shoots correspond to the fractures which cross the ore—an indication that the waters which circulated along such subsequent fractures had little effect in the redistribution of values.

9. *Philipsburg, Mont.*—The Philipsburg quadrangle is an area of sedimentary rocks, ranging from pre-Cambrian to late Cretaceous, with intrusions of quartz-monzonites and related rocks, probably belonging to the same period of intrusion as that of the Butte granites and other batholiths in Montana. The most important ore-deposits in this quadrangle are those of the Granite-Bimetallic and the Cable mines.

The Granite-Bimetallic is a strong fissure-vein in quartz-monzonite, which carries chiefly silver, but also an important amount of gold. There is conclusive paragenetic evidence of the secondary enrichment of silver below the water-level, and the rich silver-ore carries also more gold than the low-grade silver-ore in the bottom of the mine. The outcrop of this deposit carried some silver, but very little gold; and, after the discovery, the location was allowed to lapse, by reason of the small assay-returns from the gossan. Richer ore appeared not far below the surface and extended down to the 10th level. The shoot of high-grade ore, which extended for about a mile along the strike of the deposit, followed, in a broad way, the present rugged surface. The gangue is rich in manganese. Some migration of gold has undoubtedly taken place. No associated placers have been developed.

At the Cable mine the deposits are included in a long, thin block of limestone, in contact on either side with quartz-monzonite. The principal minerals are calcite, quartz, pyrrhotite, pyrite, magnetite, and chalcopyrite, with chlorite, muscovite, and other silicates. At one or two places small traces of manganese dioxide have been noted in the oxidized ore, but it is very much less abundant than in the deposits of the Granite-Bimetallic type. This deposit yielded important placers. Good ore was found at or very near the surface; and, according to the best obtainable data, the values increased somewhat for a short distance below the surface. Some concentration has

taken place by the removal of calcite and other valueless material more rapidly than gold; but there is no evidence of secondary enrichment in gold below the water-table. The indications are, that the gold has not been extensively transported since the deposit was formed.

10. *Other Montana Districts.*—The secondary enrichment of gold- and silver-deposits at Neihart, at Butte, and in other Montana districts, has been described by W. H. Weed, in various papers. These deposits generally contain appreciable manganese. In that respect they differ from the Idaho deposits described by Lindgren, which do not carry rhodochrosite or appreciable manganese dioxide. With some notable exceptions, such as the De Lamar deposits, the Idaho veins are probably older than those of Montana, and, as Lindgren has pointed out, should be grouped with the early Cretaceous California gold-veins rather than with the late Cretaceous or early Tertiary group, to which most of the Montana deposits belong. The Idaho veins which have been closely studied do not give evidence of the downward migration of gold.

11. *Edgemont, Nev.*—The gold-deposits at Edgemont, Elko county, Nev., which should be classed with group 3, are in an area of quartzite, with intrusions of granodiorite. The deposits are fissure-veins, and their gold-values are comparatively uniform. The ore consists of pyrite, galena, and arsenopyrite in a gangue of quartz. Copper carbonates and manganese-minerals are rare or absent. The ore is stoped practically to the surface. There has probably been a slight amount of enrichment by removal of certain substances in the oxidized zone more rapidly than gold; there is no evidence that gold has been transferred below the water-level by descending surface-waters.[81]

12. *Leadville, Colo.*—The deposits of Leadville yield silver, lead, and gold. The country is an area of Palæozoic limestones and quartzites, with intrusive sills and dikes of porphyries.[82] Some of these deposits carry in the upper horizons a large amount of manganese; and this ore is frequently rich in silver, presumably in the form of the native metal or as chloride.

[81] W. H. Emmons, *Bulletin No.* 408, *U. S. Geological Survey* (1910).

[82] S. F. Emmons, Geology and Mining Industry of Leadville, Colorado, *Monograph No. XII., U. S. Geological Survey* (1886); and S. F. Emmons and J. D. Irving, *Bulletin No.* 320, *U. S. Geological Survey* (1907).

Assays of this ore, showing the amount of gold contained in it, are not available to me. According to the requirements of the theory under investigation, it would be expected to be low in gold in this upper zone, where the waters probably carry ferric salts and chloride. Of considerable interest in this connection are some small fractures in the quartzite at a lower horizon, which, as Mr. Emmons informs me, often carry small amounts of high-grade manganiferous gold-ore. This ore he regards as a deposit from descending waters. Possibly it is the gold leached out above, where ferric salts predominate, and was carried to greater depth by the manganiferous solutions which delay the action of ferrous sulphate as a precipitant of gold.

13. *Georgetown, Colo., Silver-Lead Deposits.*—The silver-lead lodes of Georgetown and Silver Plume, Colo., are of early Tertiary age. The veins cut crystalline schists and Tertiary igneous rocks. According to Spurr, Garrey and Ball,[83] several thousand feet of overlying rocks have been eroded since the ores were deposited, and some of the values in the eroded portions of the lodes have migrated to the portions still remaining. The principal metallic minerals are argentiferous galena and blende, with pyrite and chalcopyrite; the ores usually carry about $2 gold per ton. The silver-values are mainly in polybasite, freibergite, argentite, pyrargyrite, and proustite. The gangue is quartz, chalcedony, barite, with carbonates of lime, iron, manganese, and magnesia.

The rich silver-minerals were the last to be deposited, and form on the walls of the fractures in the older, baser ore, or cut the older deposits. The zone of complete oxidation extends from 5 to 40 ft. below the surface. The oxidized ore often contains several hundred ounces of silver per ton. Below this ore are friable black sulphides and secondary galena. This secondary ore, according to Spurr and Garrey, is rich in silver and lead and carries more gold than occurs at greater depth. This ore cuts the primary sulphide; and the latter, which may have contained from 20 to 30 oz. of silver per ton, is enriched to more than 200 oz. per ton.

Quoting from Spurr and Garrey:[84]

[83] *Professional Paper No.* 63, *U. S. Geological Survey*, p. 136 (1908).

[84] J. E. Spurr and G. H. Garrey, *Professional Paper No.* 63, *U. S. Geological Survey*, p. 144 (1908).

"Below the zone where soft secondary sulphides occur and irregularly overlapping the lower portion of this zone the rich ores contain polybasite, argentiferous tetrahedrite, and ruby silver, better crystallized and more massive than the pulverulent sulphides, but also subsequent in origin to the massive galena-blende ore. These richer ores diminish in quantity as depth increases, though gradually and irregularly, so that the lower portion of the veins contains relatively less silver and lead. The best ore in most veins has been found in the uppermost 500 feet, although good ore extends locally down to 700 or 800 feet, and in the Colorado Central, and to a minor extent in other veins, down to a thousand feet or more."

14. *Auriferous Deposits of the Georgetown Quadrangle, Colorado.*—The auriferous deposits of the Georgetown quadrangle are mainly at Idaho Springs and in the Empire district, although some are developed near Georgetown in the area of the silver-lead deposits. As shown by Spurr and Garrey, the gold-lodes are probably of later age than the silver-lead deposits. They cut the crystalline schists and the Tertiary porphyries, but are genetically related to alkali-rich intrusive rocks of middle or late Tertiary age. They carry pyrite, chalcopyrite, chalcocite, quartz, adularia, and gold, with minor amounts of barite, fluorite, telluride, etc. Carbonates of iron, magnesium, lime, and manganese occur, but are relatively rare. In many of the mines the ore averages from 1 to 2 oz. of gold and from 20 to 40 oz. of silver per ton. The lodes are usually oxidized at the surface and from 15 to 70 ft. downward. They have yielded some moderately-productive placers. In several mines, the oxidized is much richer than the average ore. Below the zone of oxidation, secondary chalcopyrite and chalcocite prevail for several hundred feet from the surface, but decrease at greater depth. There is an important enrichment of gold and silver, coincident with the occurrence of the copper-minerals. As stated by Spurr and Garrey:

"In the mines mentioned a portion of the copper which has contributed to the enrichment of the original sulphides has been derived from the oxidized zone, but it seems unlikely that this has been the case with the gold and silver, which, like the enriched superficial portions of the argentiferous veins, must have been derived from the overlying portions of the lodes which are now eroded. . . .

"On the whole, the strongest evidence of the reworking of the ores by surface waters is afforded by markedly cupriferous ores. . . . Apart from this, however, and from the probable partial reconstruction of galena near the surface in some mines, the evidence of rearrangement of the ores by descending waters is in general not nearly so great as in the Georgetown district, and such reworking has probably taken place to a considerably less extent."

15. *San Juan, Colo.*—The gold-deposits of the San Juan region,[85] including those near Telluride, Silverton, and Ouray, are, as shown by Ransome, of varied character. They are mainly Tertiary, and should be classed with group 3 or 4 above named. The lead-silver deposits and the stocks near Ironton are not here considered.

In this elevated area the ground is frozen much of the year, and the rapid erosion is due largely to mechanical disintegration. Secular decay or oxidation of the ores, according to Ransome, is not as a rule very extensive, and is at some places negligible. Purington has pointed out, however, that the outcrops of the San Juan lodes are, in general, of lower grade than the ore a few feet below the surface, possibly by reason of the migration of gold in suspension. Many of the lodes are tight, and do not appear to offer favorable conditions for downward migration of waters. The country is well drained, and chlorine is probably not abundant in the mine-waters. The conditions for deep-seated enrichment are therefore not particularly favorable, although some concentration has taken place locally by the leaching and removal of the less-valuable materials from the ore. The workable ore appears to be mainly of primary origin.

At some places the gangue includes manganiferous minerals. There is some evidence that gold was transported to a limited extent. As Ransome points out,[86] in the Tomboy and Camp Bird mines, black oxide of manganese occurs in the deepest workings (in 1901) and usually indicates good ore. These little sheets of rich, dark, manganiferous ore, which fill post-mineral fractures, Ransome regards as later than the general mass of the ore. It is reasonable to suppose that they represent the deposition from solutions which dissolved gold in the upper portion of the lode, where ferric salts prevail, and which, in the presence of manganese, were able to transport their load to greater depths, but which, coming into contact with pyrite,

[85] F. L. Ransome, A Report on the Economic Geology of the Silverton Quadrangle, *Bulletin No.* 182, *U. S. Geological Survey* (1901); and C. W. Purington, Preliminary Report on the Mining Industries of the Telluride Quadrangle, *Eighteenth Annual Report, U. S. Geological Survey*, Part III., p. 745 (1896–97); Purington, Woods, and Doveton, The Camp Bird Mine, Ouray, Colo., *Trans.*, xxxiii., 499 to 550 (1902).

[86] *Op. cit.*, p. 101.

were ultimately reduced and forced to give up their gold when, through the oxidation of pyrite, ferrous sulphate had been formed.

16. *Cripple Creek, Colo.*—The gold-deposits of Cripple Creek, Colo., have yielded some $200,000,000 gold and less than $1,000,000 silver. The lodes are fissure-veins and replacement-deposits in volcanic breccia, in Tertiary intrusive rocks, and in granite. The fissures, according to Lindgren and Ransome,[87] were formed at about the same time as the intrusion of associated basic dikes, and represent a late phase of volcanic activity. The deposits are probably of middle or late Tertiary age, and were formed by hot ascending waters, relatively near the surface. Calaverite is the chief primary constituent; native gold is rarely present in the unoxidized ores. Pyrite is widely distributed; tetrahedrite, stibnite, and molybdenite are sparingly present. The gangue is quartz, fluorite, adularia, carbonates (including rhodochrosite), some sulphates, etc. Some of the deposits were workable at the surface, but the placers which have formed are relatively unimportant. Although rhodochrosite is subordinate in amount, the highly-fractured country-rock contains appreciable manganese (0.20 ± per cent.). According to Lindgren and Ransome, the processes of oxidation were attended by the formation of kaolin, hydrous silica, and oxides of iron and manganese. Manganese oxides are often present in the oxidized zone, and, according to Penrose, form nodules in the Pharmacist and Summit mines. They result from the alteration of rhodochrosite, manganiferous calcite, or other minerals, and are generally distributed in the oxidized zone as stains filling cracks and fissures.[88] During oxidation, manganese is greatly concentrated in the seams of the rock. In general, the lower part of the zone of oxidation is above water-level, and usually less than 200 ft. below the surface. In some places silver has been completely leached from the oxidized ores. Horn-silver is not noted.

Whether a slight enrichment of gold has taken place in the oxidized zone it is not easy to decide. Lindgren and Ransome are inclined to the belief that the oxidized zone as a whole

[87] *Professional Paper No. 54, U. S. Geological Survey* (1906).
[88] *Idem*, p. 123.

is somewhat richer than the corresponding telluride zone.[89] If this is true, no extensive downward migration of gold can have taken place. The trivial enrichment in the oxidized zone may have resulted from the removal of some constituents of the primary ore.

If gold was dissolved in the Cripple Creek deposits, it was precipitated again at practically the same horizon; for, in these deposits, the zone in which solution takes place is as rich or richer than that in which precipitation usually takes place. The ground is open, providing paths for downward-circulating waters, but it should be remembered that, while the ore-bearing complex is very pervious to water, it is surrounded by impervious rocks. After the volcanic rocks had been drained in mining, the flow of water was comparatively small. Lindgren and Ransome have compared the volcanic complex to a "sponge in a cup." As shown by them, the conditions for a circulation of atmospheric water were most unfavorable—a fact which had an important bearing on their conclusion that the ores had been formed by magmatic waters. In the absence of a circulation, the gold could not be transported. A check to this reasoning with respect to a downward circulation is the fact that in the porous, brecciated mass, filled with stagnant water, the oxidation extended downward to a depth generally less than 200 ft., and even in this zone residual sulphides are often present. If the solutions did not carry oxygen downward, it would be supposed that they could not carry gold; and if the latter had been dissolved at the higher levels, in the absence of a circulation it could not descend. There is some evidence which may be interpreted as an indication that the gold migrated laterally, or possibly that it has been precipitated essentially in place from cold solution. Richard Pearce[90] has recorded analyses of oxidized and unoxidized ore. The material for the analyses was taken from a section drawn clear across the two different portions of the specimen. The analyses show that the oxidized ore carries 14.58 oz. of gold per ton, or 2.34 oz. more gold than the unoxidized ore, and that all the silver has been leached out. In ore so rich such a con-

[89] *Professional Paper No.* 54, *U. S. Geological Survey*, p. 203 (1906).

[90] Further Notes on Cripple Creek District, *Proceedings of the Colorado Scientific Society*, vol. iv., pp. 11 to 16 (1894–96).

centration may result merely from leaching-out of the substances other than gold; but, on the other hand, the analyses of the altered rock indicate that little leaching of the silicate minerals has taken place, and that the oxidized portion was originally richer than the unoxidized, or else that some gold had been added. Since 0.27 per cent. of MnO_2 is present in the oxidized ore, while none is reported in the unoxidized ore, it appears that MnO_2 was added in the process of secondary alteration, and it is possible that the same solutions added gold and iron.

If the gold was dissolved in the Cripple Creek "sponge," it was precipitated in the stagnant solutions where they were in contact with pyrite. In the absence of a downward circulation of water, such lateral migration would not be unlikely.

The results of oxidation processes are described as follows:[91]

"Thorough oxidizing decomposition will destroy the original structure of this vein. In sheeted lodes with many small parallel fissures and joints the latter may become effaced and the lode appears as a homogeneous brown, soft mass. In other cases a central seam may be retained and usually appears as a streak of soft, more or less impure kaolin; in other cases it may be filled by white compact alunite, more rarely by jasperoid or opaline silica. Crusts of comb quartz, if originally present, lie included in the clayey seams, but neither the original fluorite nor the carbonates are ordinarily preserved. Very rich oxidized ore sometimes fills the central cavities of the lode like a thick brown mud of limonite, kaolin, and quartz sand, and easily flows out when the vein is opened."

It should not be inferred, however, where channels are large and open that the rich, gold-bearing brown mud is necessarily a deposit from solution. It may have been carried down in suspension; for similar rich mud, with 2 oz. of gold per ton, was found on the floor of the 12th level of the Gold Coin mine after it had been filled with water and allowed to stand.

It thus appears that the conditions at Cripple Creek, which at first appear fatal to the hypothesis, may be rationally explained, when it is recalled that downward migration of gold depends not only upon solution and precipitation, but requires a circulation, and that conditions for a circulation here were peculiarly unfavorable. They show also that conditions for a relatively rapid circulation are prerequisite, if the dissolved gold is to be carried below the zone of mixed oxides and sulphides.

[91] *Professional Paper No. 54, U. S. Geological Survey*, p. 199 (1906)

17. *Summit District, Colo.*—This district is located southwest of Alamosa near the Rio Grande-Conejos county-line. According to R. C. Hills,[92] the metal-bearing horizon is near the middle of the Tertiary eruptive series of south and southwest Colorado. The associated rocks are andesites, trachytes, rhyolites, etc.; but, unlike the eruptives of most Tertiary districts in this province, these rocks appear to have been closely compressed, yielding a series which, as shown in Mr. Hills's sketches, are probably isoclinals. Some features of the ore-deposits are puzzling; but, whatever their genesis, they illustrate very clearly the theory of secondary enrichment—a fact which was fully recognized by Mr. Hills as long ago as 1883.

The ore-bodies, so far as exposed, are rudely tabular and approximately vertical. The ore is chiefly quartz and pyrite, but contains some enargite, galena, sphalerite, and other minerals. Placers appear to be of subordinate importance. The mineralized matter may be separated into three divisions: (1) the impoverished zone near the apex; (2) the zone of rich and partly-oxidized ore; and (3) the low-grade sulphides. The zone of impoverishment, with two exceptions, includes the outcrops of all the lodes and extends downward to 50 ft. or more. The zone of incompletely-oxidized ore extends to a depth varying from a few feet to 300 ft. In this zone the quartz is colored dark brown by oxides, and the more-highly auriferous material is characterized by an abundance of brown oxide. The gold in this ore carries only about 0.025 silver. All the bonanzas were, according to Mr. Hills, confined to this zone. In some places gold appears in a disseminated form in innumerable small grains, so aggregated as to resemble a continuous sheet of metal. Locally, the grains unite and form flat nuggets, one or more ounces in weight. The occurrence of this richer material is confined, according to Mr. Hills, to the immediate vicinity of a central channel which has been filled with earthy matter, fragments of rock and iron oxides. Some of the rich seams of gold powder have been introduced into fractures which cut barite. Below the rich and partly-oxidized ore, the primary sulphides appear to have been unworkable under conditions then existing. There is, however, in three mines[93] a concentration of silver at greater depth than that of

[92] *Proceedings of the Colorado Scientific Society*, vol. i., p. 20 (1883–84).

[93] *Op. cit.*, p. 35.

the gold-bonanzas. Mr. Hills ascribes the two rich outcropping ore-bodies, which are exceptional in this district, to intense kaolinization on either side of the ore-bodies, causing the country-rock to be much more readily eroded than the extremely hard quartz outcrop. This consequently remained considerably above the general surface, forming a precipitous ridge, which was, as he explains, protected from solution, which went on more vigorously below, in the places where snow and water accumulated.

Although Mr. Hills mentions brown oxides at several places, he does not say that they are manganiferous.

Dr. Raymond [94] says that the oxides include those of purplish hue.

18. *Bodie, Cal.*—The deposits of Bodie, Cal., are east of the Sierras, near the State-line. They are not of the California type, but are associated with andesite and belong to the late Tertiary group so extensively developed in Nevada. R. P. McLaughlin [95] has described the most important mines. The lodes are fissure-veins in andesite. Nearly all strike northward and are approximately parallel. The ore carries about equal amounts of gold and silver. The deposits are developed extensively to a depth of 500 ft. below the surface. One shaft is 1,000 ft., another 1,200 ft. deep. Outcrops of encouraging value are rare. Almost without exception the veins have failed to carry pay-ore beyond 500 ft. below the surface; but above this depth occur large, rich ore-bodies, which, according to McLaughlin, carry ore worth as high as $400 a ton. Faulting and displacement are probably of later date than the period of vein-formation. Some of the oxidized ore carries manganese dioxide. It is "loose and clayey in texture and carries some silver to the exclusion of gold." [96]

19. *Exposed Treasure Mine, Cal.*—The Exposed Treasure mine,[97] which is near Mojave, has produced considerable gold and silver. It is in an area of granitic rocks cut by quartz-porphyry and capped by rhyolite. The lodes are probably Tertiary (group 4). The Exposed Treasure vein dips about 45° E. and is a sheeted brecciated zone. Considerable fissuring has taken place since the ore was deposited.

[94] *Mines and Mining West of the Rocky Mountains*, vol. x., p. 329 (1875).
[95] *Mining and Scientific Press*, vol. xciv., No. 25, p. 796 (June 22, 1907).
[96] *Idem*, p. 796.
[97] Courtenay De Kalb, *Trans.*, xxxviii., 310 to 320 (1907).

". . . While the lodes are continuous, and often of great width, sometimes being 40 ft. and more from wall to wall, the pay-streaks, from 4 to 15 ft. in width, lie in well-defined chutes and overlapping sheets or lenses. It is noteworthy that only those chutes or lenses which now reach the surface contained important quantities of calcite and manganese dioxide."

The oxidized ores contain much MnO_2, the concentrates carrying 12 per cent. In the altered oxidized ore are kernels of ore containing pyrite, chalcopyrite, galena, and sphalerite, and these are richer in the precious metals than the altered friable ore. As observed by De Kalb:

". . . The altered ore bore manifest signs of extensive leaching, and where it had become almost completely decolorized by the removal of iron, the precious metal contents had nearly disappeared, and such ore never contained copper except in the form of chrysocolla.

"The absence of sulphides in all the [oxidized] ores, except in the cherty skeletons, and in the undecomposed kernels of hard ore, was very complete. The mill-concentrates (150 into 1) had an average composition of SiO_2, 30; FeO, 37 . . . and MnO_2, 12 per cent. These concentrates never contained more than 1.5 per cent. of sulphur.

"In the lower friable siliceous ores, the ratio of gold to silver was as 1 to 12, while in the upper mangano-calcite ores the ratio was 1 to 72. Assays of gold-scale, and of coarse gold panned out, from all parts of the mine, showed a remarkably uniform alloy of 1 part of gold to 0.461 part of silver. The silver in the upper portion of the mine was present almost wholly in the form of silver chloride.

"On the assumption, from the evidence, that the abundance of chlorides would prevent the leaching-out of the silver and its reconcentration below water-level, and that the ferric and cupric sulphates would have abstracted large quantities of the gold, which would be re-deposited lower down together with the copper in the form of secondary enrichments, it was natural to predict an ore below permanent water rich in these metals, and relatively lean in silver. It would be difficult to conceive a nicer justification of theory than that which was afforded when development at length extended below water-level. The ore consisted of a hard bluish-gray mass of original chert-cemented breccia, re-cemented by quartz, with partial replacement of the granite and quartz-porphyry by silica, heavily impregnated with sulphides, among which were considerable quantities of chalcopyrite, bornite, and some covellite. The gold-content of the ore had increased 150 per cent. above the average in the friable siliceous ores on the upper levels, and the ratio of the gold to silver was as 1 to 2."

20. *Tonopah, Nev.*—The deposits at Tonopah, Nev., are silver-gold replacement-veins in andesite. They are of middle or late Tertiary age, but possibly somewhat older than the Comstock lode. Placers are not developed. The primary ore, according to J. E. Spurr,[98] is composed of quartz, adularia, sericite, carbonates of lime, magnesia, iron, and manganese, with argentite, stephanite, polybasite, chalcopyrite, pyrite, galena,

[98] *Professional Paper No. 42, U. S. Geological Survey*, p. 90 (1905).

blende, silver selenide, and gold in an undetermined form. The zone of oxidation extends to greater depth in the more highly fractured places; and for this reason the brittle and more broken lodes are more deeply oxidized than the wall-rock. The Mizpah vein is for the most part oxidized to a depth of 700 ft. Standing ground-water is lacking. The oxidized ore contains limonite and manganese dioxide, with plentiful horn-silver and some bromides and iodides of silver. The so-called oxidized ore from the outcrop down is, according to Spurr, a mixture of original sulphides (and selenides), together with secondary sulphides, chlorides, and oxides. At a depth of 500 ft. (in the Montana Tonopah mine) good crystals of argentite, polybasite, and chalcopyrite have been formed freely in cracks and druses of the sulphide ore. These minerals are later than the massive ore; but it cannot be shown that they were not deposited upon it by ascending waters. The case of dark ruby-silver (pyrargyrite) is different, however, for this is formed in cracks in the oxidized ore, and some argentite fringes minute particles of horn-silver as if secondary to it. "The evidence therefore favors the view that these secondary sulphides in the oxidized zone originated from descending surface waters, and probably part, but not all, of the sulphides in druses in the sulphide ore have a similar origin."

The waters which descend through the oxidized zone carry sulphates and chlorides, and "wad" is plentiful; but judging from the fairly-constant proportion of gold to silver (about 1 to 100 by weight) there has been little selective migration of gold and silver during oxidation, although the vein has been enriched to some degree by downward penetration of minerals leached from the outcrop as it was eroded. The rich ore-shoots, though partly oxidized, seem to be in the main original without thorough rearrangement. According to Mr. Spurr, this may be ascribed in part to the relatively scanty supply of water in this arid region.

21. *Goldfield, Nev.*—The ledges of Goldfield are in middle or late Tertiary rocks, and, according to F. L. Ransome, were probably deposited within 1,000 ft. of the surface at the time of deposition. Ransome states convincingly the hypothesis that these deposits were formed by hot ascending solutions which mingled with descending sulphate-water contaminated

by the oxygen of the air. Although the deposits are probably the most remarkable bonanzas of native gold-ores carrying little silver which have yet been discovered, it does not appear that they have been enriched to any considerable extent since they were deposited, for, as remarked by Ransome, it is difficult to harmonize the extent and intensity of alunitization which accompanies the gold with the hypothesis of the oxidation and enrichment of lean deposits during erosion. The mine-waters are rich in sulphates; and, judging from the geographical position of the deposits, they probably carry chlorides. Manganese dioxide is practically unknown in these ores, which in this respect differ from the ores at Tonopah and from a great many Tertiary deposits of the Great Basin province. No workable placer-deposits have been discovered; yet notwithstanding the fact that there may have been several hundred feet of vein-matter removed from these deposits since they were formed, there is little reason to suppose that much gold has migrated into the existing bonanzas from above. The gold is very finely divided, and could easily have been scattered, if it had been eroded with the ledges. As shown by the analyses of deposits elsewhere that were formed close to the surface by ascending hot waters, they seldom carry much gold. The maximum deposition is lower down; for, as soon as the ascending hot waters are contaminated by ferrous sulphate from the surface, gold must be precipitated.

The evidence offered at Goldfield is not out of harmony with the conclusion that, in the absence of manganese, gold is not readily transported in mine-waters.

22. *Manhattan, Nev.*—The gold-deposits at Manhattan, although inclosed in schists, are in an area of Tertiary volcanic activity, and should be classed with the deposits formed in Tertiary times. Although the schists contain stringers of gold of uncertain genesis, the principal deposits are steeply-dipping lodes of quartz and calcite, stained with iron and manganese oxides. Some placers are developed. Rich ore was found very near the surface, but it was richer a few feet below the outcrop than at the surface. Some fracturing has taken place since the deposits were formed. In many instances the gold of the pockets of rich ore is intimately associated with iron and

manganese oxides.[99] In view of the fact that the unaltered sulphides had not been encountered when the mines were visited, the character of the primary ore is unknown to me.

23. *Annie Laurie Mine, Utah.*—The Annie Laurie mine,[100] 175 miles south of Salt Lake, is in an area of dacite, rhyolite and rhyolite-tuff, and probably belongs to the later Tertiary group. The vein is poorly exposed at the surface, being largely covered by morainal material. Mr. Lindgren says:

"The quartz forms an almost continuous sheet along the vein, rarely less than 3 feet in thickness and often expanding to a width of 20 feet or more. As a rule the walls are poorly defined and slickensides indicating motion are rare. In places it contains, parallel to the walls, streaks of iron oxides and black, sooty, manganese ores. . . .

"The mine-workings have not penetrated below the zone of oxidation, and neither the quartz nor the country-rock seem to contain any unoxidized sulphides."

In the absence of extensive post-mineral fracturing, one would suppose that the conditions for migration of gold were not particularly favorable. Since the workings had not penetrated sulphide ore at the date of Lindgren's report, direct evidence was lacking.

24. *The Bullfrog District, Nev.*—In the Bullfrog district[101] the principal deposits are fissure-veins in rhyolite. The minerals include pyrite, quartz, and manganiferous calcite. Enough manganese is present in the calcite to stain much of the oxidized ore chocolate-brown or black. No placers are developed. The outcrops were comparatively poor, but within a few feet of the surface good ore was encountered, and some of the deposits were worked by open-cut. Some of the ore-deposits decrease in value below the 400-ft. level, where ore carrying less than $5 per ton is encountered. Since the ore above this level carried many times this value, it appears that there has been a secondary concentration by surface-waters, and that the rich ore is related to the present topographic surface.

25. *Gold Circle, Nev.*—The deposits of Midas, Gold Circle[102]

[99] G. H. Garrey and W. H. Emmons, *Bulletin No.* 303, *U. S. Geological Survey*, pp. 84 to 93 (1907).

[100] Waldemar Lindgren, *Bulletin No.* 285, *U. S. Geological Survey*, pp. 87 to 90 (1906).

[101] Ransome, Emmons, and Garrey, *Bulletin No.* 407, *U. S. Geological Survey* (1910).

[102] W. H. Emmons, *Bulletin No.* 408, *U. S. Geological Survey* (1910).

district, are in an area of late Tertiary rhyolites. The lodes are replacement-veins and sheeted zones and carry considerably more gold than silver (value). In the oxidized zone some of the ore is rich, but the sulphides are comparatively regular in value and give no evidence of extensive secondary enrichment. Some oxidized ore-shoots appear to have been increased in value by the removal of substances more soluble than gold. The minerals are chiefly quartz and pyrite. In the oxidized zone are seams of very rich gold-ore, composed of manganese, limonite, kaolin, and soft hydrous silica.

26. *Delamar Mine, Nev.*—The Delamar mine, in southeastern Nevada, is in quartzite cut by porphyry dikes of acid composition. It is presumably a Tertiary deposit, and is provisionally classed with group 4. The ore-body described by S. F. Emmons [103] is related to a strong zone of fracturing which strikes with the quartzite, but dips about 75°, or nearly at right angles to the dip of the quartzite. The ore is in shoots, or zones of crushed quartzite. The chief ore-body, which is, roughly speaking, a long and comparatively thin, nearly upright cylinder, is divided into four parts by a dike of quartz-porphyry and a more basic dike, which cross nearly at right angles in the ore-body. The ore follows the line of intersection of the two dikes rather closely. The ore at the bottom of the mine consists of quartz and pyrite, which fill fractures in the altered quartzite. Where the dikes cross in the ore-body the light-colored dike appears to be continuous, but notwithstanding this the line of the dark dike across the light one is generally marked by a slight stain of manganese dioxide, which, as stated by Mr. Emmons, is characteristic of the "black" dike, and perhaps gives it that name.

Oxidation extends as far down as the tenth level. The ore that has been found below that level is too poor in grade to pay for mining. The gold-ore carries silver and some copper. The tenor in gold increased from the surface downward to about the 7th level, although the values were not evenly distributed. Some lots of ore ran as high as 30 oz. per ton, and the richer parts of the mine averaged from $30 to $70 per ton. At the 10th level they had decreased to $4 or $5 per ton.

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[103] *Trans.*, xxxi., 658 to 675 (1901).

COGNATE PAPERS NOT REPUBLISHED IN THIS VOLUME.

Many papers which were considered for printing in this volume were not chosen because, though possessing merit, their material did not seem to constitute essential additions to the science of ore-deposits. A brief statement with regard to each is here given.

The Detection and Estimation of Small Quantities of Gold and Silver. By Luther Wagoner, San Francisco, Cal. (Mexican Meeting, November, 1901. *Trans.*, xxxi., 798–810.)—This paper contains some determinations of small amounts of gold and silver in rocks and in sea-water by Luther Wagoner, which in part confirm and in part differ from those already given by Don. It is for chemists to determine, in the case of such differences, which of the two is the more trustworthy, primarily by a discussion of methods, but more satisfactorily by a new series of determinations. In such work, the practical impossibility of procuring reagents that are absolutely free from silver or gold is a serious handicap.

The Geology and Copper-Deposits of Bisbee, Arizona. By F. L. Ransome, Washington, D. C. (Albany Meeting, February, 1903. *Trans.*, xxxiv., 618–642.)—This paper is an abstract of the geological relations of the district, which were so accurately determined by the author that his work has served as the basis of mining since it was published. Genetically, however, the deposits are not typical. Indeed, though some contact-metamorphic minerals are found associated with the ore, the author is not willing to assign a contact-metamorphic origin to it, but contents himself with saying that it is genetically connected with the intrusion of the porphyry around the periphery near which it is mainly found. The action of sulphide secondary enrichment in the district is very clear and typical.

Some Practical Suggestions Concerning the Genesis of Ore-Deposits. By Max Boehmer, Denver, Colo. (New York Meeting, October, 1903. *Trans.*, xxxiv., 449–453.)—The author of

this paper is a practical mining engineer who does not profess to be a geologist. The value of his paper as a contribution to theoretical views on ore-genesis is impaired by the fact that some of his premises are such as would not be admitted by geologists of the present day.

Yellow Ocher Deposits of Cartersville District, Bartow County, Ga. By Thomas Leonard Watson, Granville, Ohio. (New York Meeting, October, 1903. *Trans.*, xxxiv., 643–666.)—This paper is mainly descriptive of the yellow ocher deposits of the Cartersville district of Georgia. At its close it contains the brief statement that the ore is a metamorphic replacement of quartzite by material probably derived from pyrite existing somewhere in the neighborhood.

The Garnet-Formations of Chillagoe Copper-Field, North Queensland, Australia. By George Smith, Sydney, N. S. W. (New York Meeting, October, 1903. *Trans.*, xxxiv., 467–478.)—This paper is an interesting and apparently accurate description of copper- and lead-deposits in Australia, which, from their association, are evidently of contact-metamorphic origin. The author, while suggesting the possibility of this origin, does not commit himself to a belief in it, because certain facts are to him unaccountable on that theory.

Observations on Mother-Lode Gold-Deposits, California. By W. A. Prichard, Kalgoorlie, Western Australia. (New York Meeting, October, 1903. *Trans.*, xxxiv., 454–466.)—This paper is interesting as being the views of an able Australian mining engineer on California gold-deposits along the Mother Lode. It makes, however, no addition to our knowledge either practical or theoretical.

Geology of the Treadwell Ore-Deposits, Douglas Island, Alaska. By A. C. Spencer, Washington, D. C. (Lake Superior Meeting, October, 1904. *Trans.*, xxxv., 473–510.)—This paper is an elaborate and detailed study of the famous Treadwell deposit, made in the light of eight years' exploitation, since the previous examination by Dr. George F. Becker. Except for some minor petrological changes, resulting from later developments, Dr. Spencer's conclusions as to the genesis agree essentially with those adopted by Dr. Becker.

Features of the Occurrence of Ore at Red Mountain, Ouray County, Colo. By T. E. Schwarz, Denver, Colo. (Washington Meeting, May, 1905. *Trans.*, xxxvi., 31–39.)—This paper is a criticism of Ransome's description of the Yankee Girl and adjoining mines in the San Juan district, and a contribution of interesting additional facts, by T. E. Schwarz, who was long superintendent of the mines. This mine presents one of the most interesting instances of the action of secondary enrichment by downward-circulating waters.

Genesis of the Ore-Deposits at Bingham, Utah. By J. M. Boutwell, Washington, D. C. (Washington Meeting, May, 1905. *Trans.*, xxxvi., 541–580.)—In spite of its title, this paper has been judged to be more descriptive than theoretical, inasmuch as the discussions apply only to this special group of deposits, which, like those of Bisbee, are not distinctly typical of any one particular form of genesis, and do not, therefore, constitute a definite contribution to generally applicable theories. The paper contains, however, a careful and detailed enumeration and discussion of the facts which bear upon the origin of the three classes into which the author divides the Bingham deposits.

The Origin of Vein-Filled Openings in Southeastern Alaska. By A. C. Spencer, Washington, D. C. (Washington Meeting, May, 1905. *Trans.*, xxxvi., 581–586.)—This paper is a discussion of the physical strains which may have produced the vein-openings of the regions cited, and is intended by the author to indicate certain conditions under which the deformation of rocks by their own weight might lead to the production of fractures in which vein-deposits could be formed.

Lead- and Zinc-Deposits of the Virginia-Tennessee Region. By Thomas Leonard Watson, Blacksburg, Va. (British Columbia Meeting, July, 1905. *Trans.*, xxxvi., 681–737.)—This paper is a detailed and scientific description of all the features and characteristics of these important, but little known, deposits, together with a chemical and genetic discussion. Only a single deposit mentioned is connected genetically with igneous intrusions; the others, in the opinion of the author, are concentrations, along zones of fracture (largely structural anticlines),

of material originally disseminated in the sedimentary rocks. The deposits in limestone have been formed by replacement through the agency of circulating, but not necessarily deep-seated, waters.

The Secondary Enrichment of Copper-Iron Sulphides. By Thomas T. Read, New York, N. Y. (Bethlehem Meeting, February, 1906. *Trans.*, xxxvii., 297–303.)—This paper presents the results of experiments made by the author to illustrate the reactions that go on in the process of secondary enrichment. Certain errors in the experiments are shown in the discussion by the chemist, E. C. Sullivan,[1] which throw some doubt on the accuracy of the results, but the investigation is along an important line, and is instructive, even if all the conclusions may not be accepted.

The Mojave Mining-District of California. By Charles E. W. Bateson, New York, N. Y. (Bethlehem Meeting, February, 1906. *Trans.*, xxxvii., 160–177.)—This paper is descriptive of one of the little-known mining-districts of the western mining-region of southern California, with a discussion of its general geological relations.

The Geology and Petrography of the Goldfield Mining-District, Nevada. By John B. Hastings, Denver, Colo., and Charles P. Berkey, New York, N. Y. (Bethlehem Meeting, February, 1906. *Trans.*, xxxvii., 140–159.)—This paper is the result of a reconnaissance of this important district made in May and June, 1905. It does not contain any genetic conclusions with regard to the ores. Such may be found, however, in subsequent publications of the U. S. Geological Survey concerning this district.

The Tin-Deposits of the Kinta Valley, Federated Malay States. By William R. Rumbold, Oruro, Bolivia, So. America. (London Meeting, July, 1906. *Trans.*, xxxvii., 879–889.)

The South African Tin-Deposits. By William R. Rumbold, Oruro, Bolivia, So. America. (New York Meeting, April, 1907. *Trans.*, xxxix., 783–789.)—These two papers, by the same

[1] *Trans.*, xxxvii., 893 to 895 (1906).

author, are descriptive of tin-deposits in the Kinta valley of the Malay States, and of South Africa, respectively. These descriptions are interesting because of the rarity of such deposits; but the papers contain nothing of genetic importance, though the author is inclined to consider it possible that some of the Kinta valley deposits were formed in limestone. Elsewhere[2] the author has written an important paper on the Bolivian tin-deposits, in which he disproves the hitherto generally-accepted idea that these new economically-important deposits differ genetically from tin-deposits in other parts of the world.

Geology and Mining of the Tin-Deposits of Cape Prince of Wales, Alaska. By Albert Hill Fay, New York, N. Y. (Toronto Meeting, July, 1907. *Trans.*, xxxviii., 664–682.)—This paper is a description of the tin-deposits of the Seward Peninsula of Alaska. While the tin, as elsewhere, is genetically associated with granite, some of it is found in limestone.

The Extraordinary Faulting at the Berlin Mine, Nevada. By Ellsworth Daggett, Salt Lake City, Utah. (New York Meeting, April, 1907. *Trans.*, xxxviii., 297–309.)—This paper is a complete reconstruction, by descriptive geometry, of a most remarkably faulted fissure-vein.

The White Knob Copper-Deposits, Mackay, Idaho. By J. F. Kemp, New York, N. Y., and C. G. Gunther, Clifton, Ariz. (New York Meeting, April, 1907. *Trans.*, xxxviii., 269–296.) —This paper is the description of a singular occurrence of contact-metamorphic copper-ore, which is found, not in the limestone which has been intruded by granite, but in quartz-porphyry between this limestone and the granite, the limestone itself being singularly free from contact-metamorphic products.

The Vein-System of the Standard Mine, Bodie, Cal.—By R. Gilman Brown, London, England. (New York Meeting, April, 1907. *Trans.*, xxxviii., 343–357.)—This paper is a description of a series of very productive and complicatedly-faulted gold-bearing veins in eruptive rocks.

The Ore-Deposits of the Joplin Region, Missouri. By F. L.

[2] *Economic Geology*, vol. iv., p. 329 (1909).

Clerc, Denver, Colo. (New York Meeting, April, 1907. *Trans.*, xxxviii., 320–343.)—This paper is an interesting account of this much-described region by one who has long been practically familiar with it, and whose views as to the genesis of the ores differ in some respect from those that have been published by other geologists.

Geology of the Exposed Treasure Lode, Mojave, California. By Courtenay De Kalb, Los Angeles, Cal. (New York Meeting, April, 1907. *Trans.*, xxxviii., 310–319.)—This paper is a description and discussion of the geological relations of this, the most important deposit of the Mojave district, from the genetic point of view.

The Occurrence of Nickel in Virginia. By Thomas Leonard Watson, Blacksburg, Va. (Toronto Meeting, July, 1907. *Trans.*, xxxviii., 683–697.) This paper is a description of an occurrence of nickel with pyrrhotite in gabbro, which is intrusive in crystalline schists. The author does not regard the sulphides as magmatic segregations, but as a later introduction, taking place after the whole eruptive body had been metamorphosed.

Geology of the Virginia Barite-Deposits. By Thomas Leonard Watson, Blacksburg, Va. (Toronto Meeting, July, 1907. *Trans.*, xxxviii., 710–733.)—This paper is a description of the manner of occurrence of the many and varied barite-deposits of Virginia. The author regards this mineral as for the most part the result of concentration by circulating waters of material once disseminated through the limestone.

The Promontorio Silver-Mine, Durango, Mexico. By Francis Church Lincoln, New York, N. Y. (Toronto Meeting, July, 1907. *Trans.*, xxxviii., 734–746.) This deposit is a vein in rhyolite-porphyry carrying primarily sulphides of lead and zinc with less iron and copper. The silver occurs mainly in the native state, as the result of secondary enrichment.

Ore-Deposits of the Eastern Gold-Belt of North Carolina. By W. O. Crosby, Boston, Mass. (Toronto Meeting, July, 1907. *Trans.*, xxxviii., 849–856.) This paper, descriptive of certain gold-mines, contains in the introduction a classification of the

gold-veins of this region, based on geological relations and genesis, which may prove of practical use to mining engineers in that district, if its generalizations be confirmed. The gold-deposits in the central and southern parts of the State will be found treated by L. C. Graton.[3]

The Evergreen Copper-Deposits, Colorado.—By Etienne A. Ritter, Colorado Springs, Colo. (Toronto Meeting, July, 1907. *Trans.*, xxxviii., 751–765.)—This paper describes the occurrence of original bornite in a fresh-looking eruptive rock of remarkable composition, which cuts the crystalline schists. According to the author, the copper-mineral in this dike is a pneumatolytic or sublimation-product, and has not been subjected to secondary enrichment; whereas, the copper-minerals in the adjoining schists, which include also chalcopyrite, have been secondarily enriched to chalcocite and covellite.

Genesis of the Lake Valley, New Mexico, Silver-Deposits. By Charles R. Keyes, Socorro, N. M. (New York Meeting, February, 1908. *Trans.*, xxxix., 139–169.)—This paper is a description of the geological relations of these long ago abandoned deposits with the views of the author as to their genesis—views which may not be generally accepted, but which, owing to the condition of the district, are difficult to controvert.

Borax-Deposits of the United States. By Charles R. Keyes, Des Moines, Iowa. (Spokane Meeting, September, 1909. *Trans.*, xl., 674–710.) This paper is a description by the same author of the various borax-deposits in the western part of the United States, including Death valley, Furnace canyon, and the Mojave desert, with some considerations on the chemistry of borax-deposits in general.

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[3] *Bulletin No.* 293, *U. S. Geological Survey* (1906).

A Selected List of the More Important Contributions to the Investigation of the Origin of Metalliferous Ore-Deposits.

BY J. D. IRVING, H. D. SMITH, AND H. G. FERGUSON.

CONTENTS.

	PAGE.
INTRODUCTION,	839
LIST OF ABBREVIATIONS USED,	841
LIST OF REFERENCES (Alphabetically Arranged),	847
GENERAL TREATISES ON MINERAL DEPOSITS,	908
ASCENSION THEORIES,	908
CAVITIES IN ROCKS,	909
General,	909
Pore-Spaces,	909
Amygdaloidal Cavities,	909
Fissures,	909
Joints,	909
Gash-Veins and Pitches,	910
Dolomitization-Cavities,	910
Saddle-Reefs,	910
Solution-Cavities,	910
Cavities Due to Fissility, Cleavage, and Metamorphism,	910
Depth to which Cavities may Extend and Exist. See under Depth.	
CONTACT-METAMORPHIC DEPOSITS,	910
Character and Genesis of,	910
Chemical and Physical Changes which Occur during Contact-Metamorphism,	910
Contact-Deposits of Copper,	910
Gold and Silver,	911
Cobalt,	911
Silver and Lead,	911
Iron,	911
Tin,	911
Zinc,	911
Miscellaneous,	911
CLASSIFICATION OF ORE-DEPOSITS (Chronologically Arranged),	911
DEFINITION OF TERM "ORE,"	912
DEPTH, INFLUENCE OF, ON ORE-DEPOSITION,	912
General,	912
Depth to which Cavities Extend,	912
Changes in Primary Mineralogy with Depth,	912
DESCENSION THEORIES,	912

DETRITAL DEPOSITS, ... 912
General, ... 912
Distribution of Gold in Placers, Origin of Nuggets, etc., ... 913
Gold-Placers, ... 913
Stream-Placers, ... 913
Fossil-Placers, ... 913
Australasia, ... 913
Black Hills, ... 913
California, ... 913
South Africa, ... 914
Beach-Placers, ... 914
Æolian Placers, ... 914
Tin-Placers, ... 914
Platinum-Placers, ... 914
General, ... 914
Individual Localities, ... 914
Iron-Placers, ... 914
DISSEMINATED METALS ORIGINAL IN ROCKS, ... 914
General, ... 914
In Eruptive Rocks, ... 914
In Sedimentary Rocks, ... 915
In Metamorphic Rocks, ... 915
ELECTRICAL ACTION IN ORE-DEPOSITION, ... 915
EMANATIONS FROM IGNEOUS MAGMAS, ... 915
General, ... 915
Magmatic vs. Meteoric Waters, ... 916
Pegmatitic Ore-Deposits, ... 916
Pneumatolysis, ... 916
Hydrothermal Emanations, ... 916
EXPERIMENTAL DATA APPLIED TO ORE-DEPOSITION, ... 917
FAULTS AND FAULTING, ... 917
FISSURE-VEINS, ... 917
General, ... 917
Fissures. (See especially also under "Cavities in Rocks"), ... 917
Systems of, ... 917
Origin of, ... 918
Displacements and Irregularities of. Also Relative Ages, . . . 918
Classification of Fissure-Veins, ... 918
Structure and Arrangement of Mineral Contents of Fissures, . . 918
The Filling of Mineral Veins, ... 918
GEOGRAPHIC DISTRIBUTION OF METALLIFEROUS DEPOSITS, ... 919
GEOLOGIC AGE OF ORE-DEPOSITS, ... 919
LATERAL SECRETION, ... 919
MAGMATIC DIFFERENTIATION, ... 919
General Discussion, ... 919
Applied Chiefly to Rocks, ... 919
Applied to Ore-Deposits, ... 919
Of Oxide Deposits, ... 919
Of Sulphides, ... 920
Comparison with Solidification of Slags, ... 920

METASOMATISM. See Replacement.
MINERALOGY OF METALLIFEROUS ORES, ... 920
ORE-SHOOTS, ... 921
General, ... 921
Shoots as Described in Individual Localities, ... 921
ORIGIN OF METALLIFEROUS DEPOSITS, ... 921
Historical Résumés of Literature of Ore-Deposits, ... 921
Summaries of Theories of Origin of Particular Metals, ... 921
Origin of Deposits in Particular Districts, ... 922
General Papers Dealing with the Origin of Ore-Deposits as a Whole, . 922
OXIDATION. See under Superficial Alteration.
ORE-SOLUTIONS, ... 923
Nature and Origin of the Agent of Deposition, ... 923
Processes of Deposition from Solutions, ... 923
Temperatures and Pressures of Solutions and Their Effect on the Resulting Ore-Deposits, ... 924
PRECIPITATION FROM SOLUTION. See under Ore-Solutions.
PHYSICAL CONDITIONS OF ORE-DEPOSITION. See under Ore-Solutions.
PRESSURE AND TEMPERATURE IN ORE-DEPOSITION. See under Ore-Solutions; also Contact-Metamorphic Deposits.
REGIONAL METAMORPHISM. Deposits Produced by It and General Effects on Previously-formed Deposits, ... 924
REPLACEMENT, ... 924
General Discussions, ... 924
Criteria of, ... 925
Replacement Advocated and Discussed for Individual Ore-Deposits, . 925
SEDIMENTARY PROCESSES AS ORE-BUILDERS, ... 925
Ores Supposed to be a Direct Result of Sedimentary Processes, . . . 925
Ores Supposed to be Derived by Later Concentration of Sedimentary Particles in Rocks, ... 925
SUBLIMATION, ... 926
SUPERFICIAL ALTERATION, ... 926
Ground-Water and Its Movement, ... 926
Oxidation, ... 926
Secondary Sulphide Enrichment, ... 927
UNDERGROUND WATERS, ... 927
Bibliography, ... 927
Mine-Waters, ... 927
General Discussions. 927
WALL-ROCK: EFFECT OF, IN ORE-DEPOSITION, ... 928

INTRODUCTION.

The purpose of this bibliography is to present a list of the more important contributions to the problems involved in the origin of ore-deposits. The literature of this subject has become so voluminous that it is a matter of great difficulty for any one to glance over all that is published, or even to keep informed of the appearance of new and important papers.

This difficulty is felt keenly by those whose work is exclusively concerned with the study of ore-deposits, but to a very much greater degree by mining engineers, who are chiefly occupied with business affairs, and who can spare the time only to read those books which seem immediately pertinent to the work with which they are at the moment occupied.

Much that is of great practical value has appeared of recent years on this subject; many special problems have been discussed in the literature which vitally affect not only the thought of the geologist and investigator, but the estimates of value and plans for mining development which are the work of the engineer.

The idea which is kept in view in compiling this bibliography is that of grouping together all references which refer to any particular problem in ore-deposition. Much of the literature of ore-deposits, and especially the geological reports of Federal and State surveys, is necessarily geographically arranged. While attempts to find information concerning any geographic locality, therefore, offer no difficulty, it is often extremely difficult to find discussions of any particular problem in ore-deposition. The writers have for this reason attempted in this paper to compile an index according to the problem upon which information is sought. Thus the secondary enrichment of copper-ores, the segregation of the sulphides from molten magmas, the relation of eruptive rocks to deposits of the metalliferous ores, etc., are given as headings.

The paper is arranged in two portions. In the first, is a list of the more important papers bearing either directly or indirectly on the genesis of ore-deposits. The second part is a classification and rearrangement of the list under separate headings representing the departments and elements of the subject. In this way it is possible to follow each special problem through the literature.

In presenting this list the writers wish particularly to emphasize that it makes no claim to completeness. A *few* only of many possible titles are selected. The original list of papers is, therefore, far from exhaustive. All works on non-metallic deposits have been excluded, as well as all works on general geology, except those which contain especially appropriate discussions of ore-deposits. Descriptive reports on mining-dis-

tricts which offer no conclusions on genesis, and which attempt no solution of problems connected with their description, have also been, for the most part, excluded, as their inclusion would have swelled this paper beyond all due proportion. Many references are given to books not primarily concerned with ore-deposits, as these aid in the comprehension of the problems involved. Except where omission of titles has been inadvertent, the writers assume full responsibility for the exclusion of papers which have seemed to them of minor importance.

It is hoped, therefore, that this brief theoretical index will be of service. The writers are conscious that it lacks much both in amplitude and in the selection of references, but it will in any event serve to indicate the lines on which a valuable bibliography may be compiled.

ABBREVIATIONS.

In order to economize space the following abbreviations have been used in this bibliography:

Of General Import.

Hist.—Chiefly of historic interest.

Rec.—Strongly recommended as of value in the understanding of ore-genesis.

E.—Elementary.

D.—Of no especial importance.

Des.—Mainly descriptive, and only incidentally concerned with questions of ore-genesis.

Geol.—Dealing with geological problems which, though not directly concerned with ore-deposits, have important applications to the subject.

Rev.—Review or reviewed.

Abbreviations for Periodical Publications.

Abb. K. Bayer. Akad. d. Wissc.—Abbildung der Königliche Bayerische Akademie der Wissenschaften; Munich, Germany.

Act. Soc. Española d. Hist. Nat.—Acta de la Sociedad Española de Historia Natural.

Am. Geol.—American Geologist; Minneapolis, Minn. (Merged with *Econ. Geol.*, 1906.)

Am. Jour. Sci.—American Journal of Science; New Haven, Conn.

Ann. d. Mines.—Annales des Mines; Paris, France.

Ann. d. Min. de Belg.—Annales des Mines de Belgique; Brussels, Belgium.

Ann. N. Y. Acad. Sci.—Annals of the New York Academy of Sciences; New York, N. Y.

Ann. Rept. Cal. State Min.—Annual Report of the California State Mineralogist; Sacramento, Cal.

Ann. Rept. Smith. Inst.—Annual Report of the Smithsonian Institute; Washington, D. C.

Ann. Rept. U. S. G. S.—*Annual Report of the United States Geological Survey;* Washington, D. C.

Ann. Soc. Géol. d. Belg.—*Annales de la Société Géologique de Belgique;* Liège, Belgium.

Archiv f. prak. Geol.—*Archiv für praktische Geologie;* Vienna, Austria.

Ark. Geol. Sur.—*Geological Survey of Arkansas;* Little Rock, Ark.

Aust. Min. Stand.—*Australian Mining Standard;* Sydney, N. S. W., Australia.

Australas. Inst. Min. Eng.—*Australasian Institute of Mining Engineers;* Melbourne, Victoria, Australia.

Bal. Zeit.—*Balneologische Zeitung;* Berlin, Germany.

Ber. d. K. K. Ak. d. W.—*Berichte der Kaiserlich Königlichen Akademie der Wissenschaft.;* Vienna, Austria.

Berg- u. Hütt. Rund.—*Berg- und Hüttenmännische Rundschau;* Kattowitz, Germany.

Berg- u. Hütt. Zeit.—*Berg- und Hüttemännische Zeitung;* Freiberg, Germany.

Bol. Inst. Geol. Mex.—*Boletin del Instituto Geologico de Mexico;* Mexico City, Mexico.

Bol. Soc. Geol. de Mex.—*Boletin de la Sociedad Geologica de Mexico;* Mexico City, Mexico.

Bull. A. I. M. E.—*Bulletin of the American Institute of Mining Engineers;* New York, N. Y.

Bull. Can. Dept. Mines.—*Bulletin of the Department of Mines, Mines Branch, Canada;* Ottawa, Canada.

Bull. Com. Géol. Fin.—*Bulletin de la Commission Géologique de la Finlande;* Helsingfors.

Bull. Dept. Geol. Univ. Cal.—*Bulletin of the Department of Geology of the University of California;* Berkeley, Cal.

Bull. Dept. Mines Tasm.—*Bulletin of the Department of Mines, Tasmania;* Hobart, Tasmania.

Bull. Geol. Nat. Hist. Sur. Minn.—*Bulletin of the Geological and Natural History Survey of Minnesota;* St. Paul, Minn.

Bull. Geol. Soc. Am.—*Bulletin of the Geological Society of America;* Rochester, N. Y.

Bull. Geol. Sur. W. Aust.—*Bulletin of the Geological Survey of Western Australia;* Perth, Western Australia.

Bull. N. Y. State Mus.—*Bulletin of the New York State Museum;* Albany, N. Y.

Bull. N. Z. Geol. Sur.—*Bulletin of New Zealand Geological Survey;* Wellington, N. Z.

Bull. No. Car. Geol. Sur.—*Bulletin of the North Carolina Geological Survey;* Raleigh, N. C.

Bull. Soc. Belge de Géol.—*Bulletin de la Société Belge de Géologie;* Brussels, Belgium.

Bull. Soc. Géol. de France.—*Bulletin de la Société Géologique de France;* Paris, France.

Bull. Soc. de l'Ind. Min.—*Bulletin de la Société de l'Industrie Minérale;* St. Etienne, France.

Bull. U. S. G. S.—*Bulletin of the United States Geological Survey;* Washington, D. C.

Bull. Wis. Geol. Nat. Hist. Sur.—*Bulletin of the Wisconsin Geological and Natural History Survey;* Madison, Wis.

Cal. St. Min. Bu.—*California State Mining Bureau;* San Francisco, Cal.

Can. Dept. Mines.—*Canadian Department of Mines;* Ottawa, Canada.

Can. Geol. Sur., Sum. Rept.—*Summary Report of the Canadian Geological Survey;* Ottawa, Canada.

Can. Min. Jour.—*Canadian Mining Journal;* Toronto, Canada.

Can. Min. Rev.—Canadian Mining Review; Toronto, Canada.
Cent. f. Min. Geol. u. Pal.—Centralblatt für Mineralogie, Geologie and Paleontologie; Stuttgart, Germany.
Chem. News.—Chemical News; London, England.
Compt. rend. Acad. Sci.—Comptes rendus de l'Académie des Sciences; Paris, France.
Compt. rend. Cong. Géol. Int.—Comptes rendus du Congrès Géologique Internationale. Published every three years at the place where the session is held.
Compt. rend. Soc. de l'Ind. Min.—Comptes rendus de la Société de l'Industrie Minérale; St. Etienne, France.
Denkschr. Akad. Wien.
Deut. Naturforsch. u. Aert.—Deutsche Naturforscher und Aertze Gesellschaft; Leipzig, Germany.
E. and M. Jour.—Engineering and Mining Journal; New York, N. Y.
Econ. Geol.—Economic Geology; Urbana, Ill.
Ess. Glück.—Essener Glückauf; Essen, Germany.
Field Col. Mus. Pub.—Field Columbian Museum Publications; Chicago, Ill.
Geog. Jahresheft.—Geognostiche Jahreshefte; Cassel, Germany.
Geog. Mag.—Geographical Magazine; London, England.
Geol. Centralb.—Geologisches Centralblatt; Leipzig, Germany.
Geol. För. i Stock. Förhand.—Geologiska Föreningens i Stockholm Förhandlingar; Stockholm, Sweden.
Geol. Mag.—Geological Magazine; London, England.
Geol. Sur. Ark.—Arkansas Geological Survey; Little Rock, Ark.
Geol. Sur. Can.—Geological Survey of Canada; Ottawa, Canada.
Geol. Sur. Eng. and Wales.—Memoirs of Geological Survey of England and Wales; London, England.
Geol. Sur. Ga.—Geological Survey of Georgia; Atlanta, Ga.
Geol. Sur. Gt. Brit.—Geological Survey of Great Britain; London, England.
Geol. Sur. Ky.—Bulletin of Kentucky Geological Survey; Lexington, Ky.
Geol. Sur. N. S. W.—Memoirs of Geological Survey of New South Wales; Sydney, Australia.
Geol. Sur. Queensl.—Publications of Geological Survey of Queensland; Brisbane, Australia.
Geol. Sur. So. Aust.—Report of Geological Survey of South Australia; Adelaide, Australia.
Geol. Sur. W. Aust.—Bulletin of the Western Australia Geological Survey; Perth, Western Australia.
Glückauf.—Glückauf, Essen, Germany.
Jahrb. d. K. K. Geol. Reichsanst.—Jahrbuch der Kaiserlich Königlichen Geologische Reichsanstalt; Vienna, Austria.
Jahrb. d. Kgl. Pr. Geol. Landesanst.—Jahrbuch der Königlich Preussichen Geologischen Landesanstalt und Bergakademie; Berlin, Germany.
Jahrb. d. Naturhist. Landes. in Kärnten.—Jahrbuch der Naturhistorisches Landesmuseums in Kärnten; Klagenfurt, Austria-Hungary.
Jahrb. f. Berg- und Hütt. im König. Sachs.—Jahrbuch für Berg- und Hüttenwesen im Königreich Sachsen; Freiberg, Germany.
Jour. Am. Chem. Soc.—Journal of the American Chemical Society; Easton, Pa.
Jour. and Proc. Roy. Soc. N. S. W.—Journal and Proceedings of the Royal Society of New South Wales; Sydney, Australia.
Jour. Can. Min. Inst.—Journal of the Canadian Mining Institute; Montreal, Canada.
Jour. Coll. Sci. Imp. Univ. Jap.—Journal of the College of Science of the Imperial University of Japan; Tokyo, Japan.

Jour. Geol.—Journal of Geology; University of Chicago, Chicago, Ill.

Jour. Iron and Steel Inst.—Journal of the Iron and Steel Institute; London, England.

Jour. Roy. Inst. Cornw.—Journal of the Royal Institution of Cornwall; Truro, England.

Jour. Soc. Arts.—Journal of the Society of Arts; London, England.

K. K. Ackerb. Minist.—Statistich Jahrbuch der Kaiserlich Königlicher Ackerbauministerium; Vienna, Austria.

K. K. Ak. d. W. in Wien.—Kaiserlich Königliche Akademie der Wissenschaft in Wien; Vienna Austria.

Mem. Geol. Sur. Eng. and Wales.—Memoirs of the Geological Survey of England and Wales; London, England.

Mem. Geol. Sur. Ind.—Memoirs of the Geological Survey of India; Calcutta, India.

Mem. Geol. Sur. Vict.—Memoirs of the Geological Survey of Victoria; Melbourne, Australia.

Mem. Mines Dept. Transvaal.—Memoirs of the Mines Dept. Geological Survey, Transvaal, So. Africa; Pretoria, So. Africa.

Mem Mus. Comp. Zool. Har. Coll.—Memoirs of the Museum of Comparative Zoology of Harvard College; Cambridge, Mass.

Mem. Soc. Cien. Ant. Alz.—Memorias y Revista de la Sociedad Cientifica "Antonio Alzate"; Mexico City, Mexico.

Mem. Soc. Ing Civ.—Mémoires de la Société des Ingénieurs Civils de France; Paris, France.

Min. and Sci. Press.—The Mining and Scientific Press; San Francisco, Cal.

Min. Ind.—The Mineral Industry. Published by the *Engineering and Mining Journal,* New York, N. Y.

Min. Jour.—The Mining Journal; London, England.

Min. Mag. (J).—The Mining Magazine. W. J. Johnston, publisher; New York, N. Y.

Min. Mag. (R).—The Mining Magazine. T. A. Rickard, editor; London, England.

Min. Met. Soc.—Mining and Metallurgical Society of America; New York, N. Y.

Min. Res.—Mineral Resources of the United States, U. S. Geological Survey; Washington, D. C.

Mineralog. Mag.—Mineralogical Magazine; London and Truro, England.

Mines Dept. Tasm.—Mines Department Tasmania; Hobart, Tasmania.

Mines Dept. Trans.—Mines Department Transvaal; Pretoria, South Africa.

Mitt. d. Naturwiss. Vereins f. Neuvorkommen u. Rügen.—Mittheilungen der Naturwissenshaftliches Vereins für Neuvorkommen und Rügen.

Mitt. d. Philomat. Gesel. in Els. Löthr.—Mittheilungen der Philomatischen Gesellschaft im Elsass Löthringen.

Mon. U. S. G. S.—Monograph of the United States Geological Survey; Washington, D. C.

Monatsb. d. D. Geol. Gesel.—Monatsberichte der Deutschen Geologischen Gesellschaft; Berlin, Germany.

N. Z. Inst. Min. Eng.—New Zealand Institute of Mining Engineers; Auckland, New Zealand.

N. Z. Mines Rec.—New Zealand Mines Record; Wellington, N. Z.

Nat.—Nature; London, England.

Naturf.—Der Naturforscher; Berlin and Tübingen, Germany.

Neues Jahrb. f. Min.—Neues Jahrbuch für Mineralogie, Geognosie, Geologie und Petrefactenkunde; Heidelberg, Germany.

Norsk Teknisk Tids.—Norsk Teknisk Tidsskrift; Christiania, Norway.

Öst. Zeit. f. Berg- u. Hütt.—Österreichische Zeitschrift für Berg- und Hüttenwesen; Vienna, Austria.

Phil. Mag.—Philosophical Magazine; London, England.

Poyg. Ann.—Poggendorff's Annalen der Physik und Chemie; Berlin, Germany.

Proc. Am. Acad. Arts and Sci.—Proceedings of the American Academy of Arts and Sciences; Boston, Mass.

Proc. Am. Assoc. Adv. Sci.—Proceedings of the American Association for the Advancement of Science; Washington, D. C.

Proc. Am. Phil. Soc.—Proceedings of the American Philosophical Society; Philadelphia, Pa.

Proc. and Trans. Nov. Scot. Inst. Sci.—Proceedings and Transactions of the Nova Scotia Institute of Science; Halifax, N. S.

Proc. Colo. Sci. Soc.—Proceedings of the Colorado Scientific Society; Denver, Colo.

Proc. Gen. Min. Assoc. Que.—Proceedings of the General Mining Association of the Province of Quebec; Ottawa, Canada.

Proc. Lake Sup. Min. Inst.—Proceedings of the Lake Superior Mining Institute; Ishpeming, Mich.

Proc. Roy. Soc.—Proceedings of the Royal Society of London; London, England.

Proc. Roy. Soc. Vict.—Proceedings of the Royal Society of Victoria; Melbourne, Australia.

Proc. Wash. Acad. Sci.—Proceedings of the Washington Academy of Sciences; Washington, D. C.

Prof. Paper U. S. G. S.—Professional Paper of the United States Geological Survey; Washington, D. C.

Quar. Jour. Geol. Soc.—The Quarterly Journal of the Geological Society of London; London, England.

Rept. Brit. Assoc. Adv. Sci.—Report of the British Association for the Advancement of Science; London, England.

Rept. Col. St. Bu. Min.—Report of the Colorado State Bureau of Mines; Denver, Colo.

Rept. Mich. Acad. Sci.—Report of the Michigan Academy of Science; Ann Arbor, Mich.

Rept. Mich. State Geol.—Report of the State Geologist of Michigan; Lansing, Mich.

Rept. Ont. Bu. Mines.—Report of the Ontario Bureau of Mines; Toronto, Canada.

Rev. Gén. d. Sci.—Revue générale des Sciences, pures et appliqués; Paris, France.

Rev. Univ. d. Mines.—Revue Universelle des Mines et de Métallurgie; Liège, Belgium.

Rosenb. Fests.—Rosenbusch Festschrift.

Roy. Soc. Tasm.—Royal Society of Tasmania; Hobart, Tasmania.

Sch. Min. Quar.—School of Mines Quarterly—Columbia School of Mines; New York.

Schles. Ges. f. Vater. Kult.—Schlessische Gesellschaft für Vaterlandische Kultur; Breslau, Germany.

Sci. Mon.—Scientific Monthly, published by the Colorado State School of Mines; Golden, Colo.

Sci. Prog.—Science Progress; London, England.

Science.—Science. Weekly Journal, published by the American Association for the Advancement of Science; New York, N. Y.

Sitz. d. Würz. phys. med. Gesel.—Sitzungsberichte des Würzburger physikalisch medizinischen Gesellschaft; Würzburg, Germany.

So. Af. Assoc. Eng.—Transactions of the South African Association of Engineers; Johannesburg, So. Africa.

Stahl u. Eisen.—Stahl und Eisen; Düsseldorf, Germany.

Tech. Quar.—Technology Quarterly. Published by the Massachusetts Institute of Technology; Boston, Mass.

Trans. A. I. M. E.—Transactions of the American Institute of Mining Engineers; New York, N. Y.

Trans. Aust. Inst. Min. Eng.—*Transactions of the Australian Institute of Mining Engineers;* Melbourne, Australia.

Trans. Fed. Inst. Min. Eng.—*Transactions of the Federated Institution of Mining Engineers;* London, England.

Trans. Geol. Soc. So. Af.—*Transactions of the Geological Society of South Africa;* Johannesburg, South Africa.

Trans. Inst. Min. and Met.—*Transactions of the Institute of Mining and Metallurgy;* London, England.

Trans. Int. Min. and Met. Cong.—*Transactions of the International Mining and Metallurgical Congress.*

Trans. Min. and Geol. Inst. Ind.—*Transactions of the Mining and Geological Institute of India;* Calcutta, India.

Trans. N. Y. Acad. Sci.—*Transactions of the New York Academy of Sciences*; New York, N. Y.

Trans. N. Z. Inst. Min. Eng.—*Transactions of the New Zealand Institute of Mining Engineers;* Auckland, New Zealand.

Trans. No. Eng. Inst. Min. and Mech. Eng.—*Transactions of the North of England Institute of Mining and Mechanical Engineers;* Newcastle-upon-Tyne, England.

Trans. Roy. Geol. Soc. Cornw.—*Transactions of the Royal Geological Society of Cornwall;* Plymouth, England.

Trans. So. Af. Assoc. Eng.—*Transactions of the South African Association of Engineers;* Johannesburg, South Africa.

Trans. Wis. Acad. Sci.—*Transactions of the Wisconsin Academy of Sciences;* Madison, Wis.

Tscher. Min. u. Pet. Mitt.—*Tschermak's Mineralogische und Petrographische Mittheilungen;* Vienna, Austria.

U. S. G. S.—*United States Geological Survey;* Washington, D. C.

Univ. Geol. Sur. Kans.—*University Geological Survey of Kansas;* Topeka, Kan.

Verhand. d. Naturhist. V. d. Pr. Rheinlande.—*Verhandlungen des Naturhistorischen Vereins der Preussischen Rheinlande und Westphalens;* Bonn, Germany.

Verhand. d. Würzburger Phys. Med. Ges.—*Verhandlungen der Würzburger Physikalisch-Medizinischen Gesellschaft;* Würzburg, Germany.

Verhand. Geol. Reichsanst.—*Verhandlungen der Kaiserlich-Königlichen Geologischen Reichsanstalt;* Vienna, Austria.

Wat. Sup. and Irr. Paper.—*Water Supply and Irrigation Paper, U. S. Geological Survey;* Washington, D. C.

Wis. Geol. Nat. Hist. Sur.—*Wisconsin Geological and Natural History Survey;* Madison, Wis.

Zeit. f. Angew. Chem.—*Zeitschrift für Angewandte Chemie;* Leipzig, Germany.

Zeit. f. Berg- Hütt. u. Salinenw.—*Zeitschrift fur Berg- Hütten und Salinenwesen in dem Preussichen Staate;* Berlin, Germany.

Zeit. d. D. Geol. Gesel.—*Zeitschrift der Deutschen Geologischen Gesellschaft;* Berlin, Germany.

Zeit. f. Kryst.—*Zeitschrift für Krystallographie und Mineralogie;* Munich, Germany.

Zeit. f. prak. Geol.—*Zeitschrift für praktische Geologie;* Berlin, Germany.

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Molybdenum.—*Mineral Resources Series*, No. 11, *Geol. Sur. N. S. W.* (1906). 17 pp.

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ARGALL, PHILIP.
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2. Rock Oxidation at Cripple Creek.—*Min. and Sci. Press*, vol. 96, pp. 883–886 (1908).
3. Zinc Resources of Canada. Report of the Commission to investigate the Zinc Resources of British Columbia, pp. 147–252 (Ottawa, 1906).

ARNOLD, RALPH.
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ASHLEY, G. H.
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ABBREVIATIONS.—Hist., chiefly of historic interest; Rec., strongly recommended as of value in the understanding of ore-genesis; E., elementary; D., of no especial importance; Des., mainly descriptive and only incidentally concerned with questions of ore-genesis; Geol., dealing with geological problems which, though not directly concerned with ore-deposits, have important applications to the subject; Rev., review or reviewed. The abbreviations "Rec.," "Des.," etc., are attached to only a few of the more general papers. Where omitted the paper is usually a valuable one in that particular phase of the discussion where it is cited.

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EMANATIONS FROM IGNEOUS MAGMAS.

(Ore-deposits have been conceived as arising from igneous magmas as a source and depositing ores under three different conditions: (1) As final products of differentiation or solidification of the rock mass, more or less extensively mingled with molten eruptive rock, and producing *pegmatite veins*; (2) As solutions not appreciably mingled with molten magma, *i. e.*, as *pneumatolytic* vapors, producing deposits under conditions of high temperatures and *pressures* usually conceived as produced by deep burial. When such vapors act on limestones *contact-metamorphic deposits* are produced (which see); (3) As solutions emanating from the magmas in the same way, but migrating to greater distances from them, and giving rise both to hot mineral springs, and to the usual types of ore-deposits, veins, replacements, etc. Commonly called *hydrothermal deposits* (*Hydatogenetic*). These three headings are used in classifying the following references.)

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PRESSURE AND TEMPERATURE IN ORE-DEPOSITION.

(See under "Ore-Solutions" and "Contact-Metamorphic Deposits.)

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WALL ROCK. INFLUENCE OF ON ORE-DEPOSITION.

(For influence of wall-rock on *fissure formation* see "Fissures," sub-head under "Cavities in Rocks." These references apply only to mineral contents.)

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18, pp. 165-166, 1911.
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8, 9, 1896.
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Van Hise, 4, pp. 88-91, 1900; 8, pp. 1086-1088, 1229, 1904.
Weed, 6, General, 1901.

INDEX.

[NOTE.—In this Index the names of authors of papers are printed in small capitals, and the titles of papers in italics. References to papers expressly treating of the subject named are likewise in italics; and casual notices, giving but little information, are usually indicated by bracketed page numbers.]

A., C. F.: silver sandstones of Utah, 324.
Absorption process in contact-metamorphism, 579.
Accident mine, Cripple Creek, Colo., [420].
Acidity in mine-waters: cause, 174.
Adams, F. D.: origin of nickel-ores, 482.
Age of igneous rocks; determination, 67.
Agency of Manganese in the Superficial Alteration and Secondary Enrichment of Gold-Deposits in the United States (EMMONS), xxviii, 759-828.
Aguilera, J. G.: mineral deposits of Mexico, [367].
Aguilera and Ordoñez: rocks of San Jose, Tamaulipas, Mexico, 565.
Ajax mine, Cripple Creek, Colo., [419].
Alaska, Forty-Mile district; dike-rocks, 272.
  igneous rocks, 261, 262, 263.
  gold-production, 436.
  Napoleon creek placers: origin, 300.
  Panhandle region: geology, 583.
Alaskite: crystallization process, 609.
  definition, 272, 604.
  occurrence and composition, 273.
  Silver Peak, Nev., 623.
Albite: crystallization from magmas, 609.
  in veins of Juneau district, Alaska, 588.
Alfreina mine, Cananea, Mexico, [378].
Algoma district, Ontario, nickel-deposits, 463.
Algonkian: Lake Superior region, 637.
  rocks included in, 69.
Algonkian rocks: classification, 69.
  distribution, 69.
Alkaline earths: in mine-waters, 768.
  solutions: solvent capacity, 30.
Allen, E. T.: composition of gravel at Steamboat Springs, Nevada, 631.
Allotropism of Gold (LOUIS), xv, 105-109.
Alteration: agents, 113.
  antimony-deposits, 134.
  bismuth-deposits, 134.
  copper-deposits, 128-131.
    Arizona: climatic effect, 129.
      process, 129.
  depth of, 118.
    factors controlling, 120.
  gold-deposits, 132-133.
  in fissure-veins, 532.
  lead-deposits, 131.
  manganese-deposits, 127.
  mercury-deposits, 134.
  method and chemical effects, 113.
  molybdenum-deposits, 135.
  physical effects, 116.
Alteration: silver-deposits, 131.
    Silver Cliff, Colo., 155.
  sulphides to oxides, carbonates, and chlorides, 2.
  superficial: ore-deposits, xv.
  tin-deposits, 133-134.
  varying depths from surface, 121.
  wall-rocks, Tonopah, Nev., 595.
  zinc-deposits, 131-132.
Alteration-products: classification, 123.
  technical names, 112.
Alumina: in mine-waters, 768.
  quantity in igneous rocks, 732.
Amalgamation: gold, 107.
Analyses: analcite-tinguaite, 566.
  basalt, 567.
  camptonite, 566.
  deep water from Geyser mine, Silver Cliff, Colo, 152.
  diorite-porphyry, 564.
  eruptive rocks, 705.
  gabbro, 563.
  limestone, 568.
  mine-timbers, 180.
  minerals isolated from rocks of New Zealand, 167.
  nephelite-syenite, 562.
  nickel-bearing mineral, 472, 473.
  non-magnetic residue from pyrrhotites, 472.
  ore from Geyser mine, Silver Cliff, Colo., 147.
  radioactive water, 709.
  sinter, 629.
  sinters from Geyser mine, Silver Cliff, Colo, 149.
  spring waters, 706.
  vadose country-rock: Ballarat goldfield, Victoria, 187.
    Lake Wakatipu, N. Z., 189.
    Ohinemuri district, N. Z., 190.
    Otago, N. Z., 188.
    Walhalla gold-field, Victoria, 186.
  vadose water from Geyser mine, Silver Cliff, Colo., 151.
  volcanic gas, 388.
  water, 152, 630.
  wood for gold, 198.
Anchoria-Leland mine, Cripple Creek, Colo., [420].
Andesite: Tonopah, Nev., 591.
Andradite: San Jose, Tamaulipas, Mexico, 572.
Animikie iron-range: Lake Superior region, 651.
Annie Laurie gold-mine, Utah, [827].

Anthon, E. F.: affinity of metals for sulphur, xli.
Anthracite, graphitic: association with silver-lead ores, 317.
Antimony: in silver-ore, Silver Cliff, Colo., 141, 147.
reducing power, 353, 358.
relations to igneous rocks, 754.
Antimony-deposits: alteration, 134.
Apatite: in magnetite: Kiirunavaara, 677.
Apollo gold-mine, Unga Island: gold-production, 440.
Apparatus for examining mine-waters, 180.
Aqueous solutions: ore-deposition, 29.
Archean: Lake Superior region, 637.
rocks included in, 68.
Silver Cliff, Colo., 139, 145.
Areal distribution of mining-districts, 325.
Argall, Philip: origin of Sudbury nickel-ores, 483.
Arid regions: alteration of ore-deposits, 136.
Arizona: Clifton copper-deposits, 401, 517–556.
gold-production, 440.
Arsenic: reducing power, 353, 358.
relations to igneous rocks, 754.
Arsenopyrite; in contact-metamorphic deposits of Sacrificio mountain, Durango, Mex., 402.
reducing power, 353, 358.
Arsenopyrite type of ore-deposits, 372.
Ascending meteoric waters: cause, 242.
Ascension-theory of ore-deposition, xiii, 12, 14, 15, 201.
objections to, 160.
Ashburner, C. A.: charcoal in anthracite, 319.
Assays: for determination of fineness of gold, 182.
for gold in California rocks, 301.
marine sediments, 197.
silver, [17].
Sudbury, Ontario, ores, 464.
vadose and deep vein-gold, 184.
methods, 185.
Atacamite: occurrence at Jerome, Ariz., 136.
Augite: separation from hornblende, 166.
Auric compounds: formation, 107.
Auriferous lodes; origin, 201.
Aurylic compounds: formation, 107.
AUSTIN, W. L.: *Discussion on Ore-Deposits near Igneous Contacts*, 396-402.
Discussion on The Geological Features of the Gold-Production of North America, 447-449.
contortion in wollastonite, 577.
Austin district, Nevada, ore-deposits, 617.

Bäckström; genesis of iron-ores of Norrbotten, Sweden, 678.
Ball, Spurr, and Garrey: silver-lead deposits, Georgetown and Silver Plume, Colo., [816].
Ball Mountain fault, Leadville, Colo., 48.
Ballarat gold-field, Victoria: vadose country-rock: analyses, 187.
BANCROFT, G. J.: *The Formation and Enrichment of Ore-Bearing Veins*, xxvii, 696–719; *Supplementary Paper*, 720–728.
Banded structure in ore-bearing rock: origin, 56.
Bannack, Mont., gold-deposits, 381.
Baraboo iron-range, Wisconsin: origin of ores, 651, 652.
Baric chloride: precipitant for gold, 194.
Barite: distribution in Missouri, 89.
Barite-deposits: Virginia, 834.
Barium: distribution in igneous rocks, 748.
quantity in igneous rocks, 733.
Barlow, A. E.; geology of Sudbury, Ontario, nickel-deposits, 479.
Barrell, Joseph: contact-effects in Elkhorn district, 576.
contact-metamorphism, 374, 392, 524.
physical effects, 385.
rocks of Elkhorn district: composition, 383.
Barus, Carl: compression of water, 244.
Barysphere: metals in, 714.
Baryta: tests for: in rocks at Leadville, Colo., 16-17.
Basalt: San Jose, Tamaulipas, Mexico, 567.
Basaltic rocks: Cripple Creek district, Colo., 411.
Bassick mine, Silver Cliff district, Colo., 158.
example of chimney-deposits, 58, 59.
locus of ore-bodies, 24.
BATESON, C. E. W.: *The Mojave Mining-District, California* [*Trans.*, xxxvii, 160–177], *Notice*, 832.
Batesville, Ark.: manganese-deposits: concentration, 128.
Bauxite: origin, 135.
Bayley, W. S.: absorption-phenomena at Pigeon Bay, Minn., 579.
Beck, Richard: gold-bearing granite, 367.
nickel-ores, origin, 485.
ore-deposits, [218].
genesis, [253].
Berggiesshübel, 378.
BECKER, G. F.: *Biographical Notice of Samuel Franklin Emmons*, xxix–xlvii.
The Torsional Theory of Joints, xiii, 92–104: Discussion (HOWE), 101; (RAYMOND), 101–102; (BECKER), 103, 104; (BOYD), 103.
Discussion on The Genesis of Certain Auriferous Lodes, 207–208.
bitumen associated with quicksilver, 345.
Comstock lode, 60.
production, 803.
quartz, 801.
replacement, xl.
source of ore-materials, [164].
Comstock rocks, erosion, 85.
convection currents in magmas, 260.
deposition of sulphides by hot ascending waters, 629.
investigations of country-rocks, Washoe, 23.
"linked veins," 221.
minerals in Appalachian gold-deposits, 809.
natural solvents of precious metals, xiv, [203].
osmosis in ore-formation, [xxiv].
quicksilver-deposits, [207].
genesis, 79.
vein-formation at Clear Lake, Cal., and Steamboat Springs, Nev., xiv.

"Bedded vein": definition, 36.
Bedding: agency in producing water-channels, 33.
Bell, Robert: origin of nickeliferous pyrrhotite, 481.
Belmont district, Nevada: ore-deposits, 617.
Ben Eaton mine, Silver Cliff region, Colo., 157.
Bendigo gold-field, Victoria: assays, 185.
Beresite at Belmont, Nevada, 278.
Berggiesshübel, Saxony, ore-deposits, 378.
BERKEY, C. P., and HASTINGS, J. B.: *The Geology and Petrography of the Goldfield Mining-District, Nevada* [*Trans.*, xxxvii, 140-159], *Notice*, 832.
Berner's Bay, Alaska: gold-deposits, 811.
Beryllium: distribution in igneous rocks, 746.
Bibliography: *Science of Ore-Deposits*, (IRVING, SMITH, FERGUSON), 837-928.
Scientific Publications of S. F. Emmons, xlii-xlvii.
Bibra: metals in ashes of marine plants, [256].
Big Seven mine, Neihart, Mont., 220.
Bischof, G.: derivation of vein-materials, 22.
metals in water of springs, [708].
ores in sedimentary rocks, 256.
transformation of potassium feldspar to albite, 587.
Bisilicates: metal-content, 203-204.
Bismuth: relations to igneous rocks, 754.
Bismuth-deposits: alteration, 134.
Bispberg mine, Sweden: origin of iron-ores, 670.
Bitumen: association with ore-deposits, 345.
reducing power, 305, 350, 357.
Bituminous coal: reducing power, 351, 357.
Bituminous shales: association with ore-deposits, 327.
Black Hills, S. Dak.: fissures conducting ore-bearing solutions, 700.
gold-deposits, 810.
Blair mines, Silver Peak quadrangle, Nevada, 621, 622, 624.
BLAKE, W. P.: *Discussion on The Genesis of Certain Auriferous Lodes*, 211-212.
petroleum associated with zinc- and lead-ores, 344.
Blende: deposition from mine-waters, 330.
mode of occurrence in Missouri, 327.
reducing power, 358.
Blezard (Dominion) mine, Blezard township, Sudbury district, Ontario, 499.
Block 8 of State land mine, Cripple Creek, Colo., 422.
Blue limestone, Leadville, Colo.: geologic horizon, 18.
ore-bodies in, 7, 13.
receptacle of ore-materials, 7, 16.
Bluebird granite, 223, 224.
Bodie, Cal.: gold-deposits, 823.
BOEHMER, MAX: *Some Practical Suggestions Concerning the Genesis of Ore-Deposits* [*Trans.*, xxxiv, 449-453], *Notice*, 829-830.
Bog iron-deposits: Gunnison region, Colo., 32.
Red mountain, Colo., 32.
Bog-ore: Scandinavia, 694.
Boiler-scale: examination for gold, 178-179.
Bonanzas: occurrence, 453.
Borax-deposits: formation, 115.
United States (KEYES), 835.
Bornite: reducing power, 358.
Boron: distribution in igneous rocks, 748.
Boundary district, B. C.: copper-deposits, 374.
BOUTWELL, J. M.: *Genesis of the Ore-Deposits at Bingham, Utah* [*Trans.*, xxxvi, 541-580], *Notice*, 831.
BOYD, C. R.: *Discussion on The Torsional Theory of Joints*, 103.
Breccia: in fissures, 45.
in fissure-veins: origin, 46.
Silver Cliff, Colo., 143.
Brecciation in country-rock: effect on ore-deposits, 118.
Breithaupt: derivation of vein-materials, 22.
British Columbia: Boundary district: copper-deposits, 374.
gold-production, 436.
Rossland: pyrrhotite-deposits, 462, 486.
British Guiana: gold-quartz veins, 281.
Brock, R. W.: copper-deposits of Boundary district, 375.
pyrrhotite-deposits, Rossland, B. C., 486.
Brögger, W. C.: contact-metamorphic phenomena, 525.
igneous rocks of Christiania region, 692.
origin of igneous rocks, [260].
Brokaw, A. D.: experiments on solution of gold, 763, 773, 776.
Bromine: solvent of gold, 173.
BROWN, R. G.: *The Vein System of the Standard Mine, Bodie, Cal.* [*Trans.*, xxxviii, 343-357], *Notice*, 833.
Browne, D. H.: magnetic separation of nickel-ores, 467.
nickel-ores of Sudbury, 470, 483.
Browne, Ross E.: association of gold with slate in California, 211.
Brun, Albert: experiments on lavas, 725.
gases in lavas, [767].
Buehler and Gottschalk: rôle of pyrite, 766.
Bull-Domingo mine, Silver Cliff district, Colo., 24, 58, 158.
Bullfrog, Nev.: geology and ore-deposits, 600.
gold-deposits, 827.
Bullion-Beck mine, Tintic district, Utah, 335, 336.
Bunsen, R.: volcanic gases, 723.
Burns mine, Cripple Creek, Colo., 422.
Bush, E. R.: origin of Sudbury nickel-ores, 483.
Butte, Mont.: copper-deposits: alteration, 130.
genesis, 76.
vein-formation, 55, 220.
Butte granite, 223, 224.

Cable mine, Philipsburg quadrangle, Mont., [762], 814.
character of gold-enrichment, 762.
Cadmium: distribution in igneous rocks, 753.

Calcium: in mine-waters, 768.
Calcium disulphide: reducing power, 358.
California: assays for gold, 301.
gold production, 436.
California metallographic province, 619.
California region: geologic history, 583.
Cambrian: Silver Peak quadrangle, Nevada, 604.
Camp Bird gold-mine, Ouray, Colo., [787], [818].
Camptonite: San Jose, Tamaulipas, Mexico, 566.
Cananea, Sonora, Mex.: copper-deposits, 376, 396.
volcanic action, 715.
Cananea mountains: physiographic features, 376.
Carbon: mode of occurrence, 315.
protective action, 311.
reducing action, 305.
reducing power, 307.
Carbon dioxide: occurrence in New Almaden quicksilver mine, 363.
rôle in formation of ore-deposits, 312.
Carbon monoxide: reducing power, 358.
Carbonaceous matter: influence on formation of ore, 231.
Carbonate fault, Leadville, Colo., 48.
Carbonate Queen mine, Cripple Creek, Colo., 419.
Carbonates: in mine-waters, 768.
Carbonic acid gas: in subterranean water: Silver Cliff, Colo., 148.
rôle in formation of ore-deposits, 312.
stability, 313.
Carboniferous rocks: relation to Cambrian country-rock in Ozark region, Mo., 88.
Carlyle, W. A.: gold-quartz veins in Slocan district, B. C., 280.
Carn Marth, Cornwall: banded ore-deposits, 57.
Catalytic action: definition, 309.
Caves: formation by solution, 6.
Leadville, Colo.: formation subsequent to ore-deposits, 4.
receptacles for ore-bodies, 7-8.
Cavities: ore-deposition in, 87.
Cazin, F. M. F.: origin of copper- and silver-ores in Triassic sand-rock, [326].
Cerium: distribution in igneous rocks, 749.
Chalcocite: chemical relations with pyrite, 798.
in diorite, 90.
oxidation, 534.
reducing power, 358.
Chalcocitization: vertical relation to deep-seated enrichment of gold, 798.
Chalcopyrite: formation, 310.
in Geyser mine, Silver Cliff, Colo., 146.
reducing power, 358.
relation to pyrrhotite, 513.
San Jose, Tamaulipas, Mexico, 574.
Chalcopyrite type of ore-deposits, 372.
Chamberlin and Salisbury: gases in volcanic emanations, 723.
specific gravity of earth, 715.
Chamberlin, R. T.: gases in rocks, [767].
Chamberlin, T. C.: succession of ores in lead- and zinc-deposits of Wisconsin, [407].
Chance, H. M.: coal carrying gold, 321.
Channels: conducting ore-bearing solutions, 700.
for circulating waters in earth's crust, 30.
in rock-masses: closing of, 699.
Chapeau de fer (gossan): definition, 112.
Character and Genesis of Certain Contact-Deposits [Lindgren], xix.
Charcoal in Geyser shaft, Silver Cliff, Colo., 143.
native: deoxidizing agency, 319.
Charters Towers, Queensland: rocks, 163.
Chemical changes (rocks and ore-deposits): see Alterations.
Chemical composition of beds: factor in ore-deposition, 36.
Chemical forces: rôle in solution and deposition, 30.
Chemistry of Ore-Deposition (JENNEY), xxii, 305-363; *Discussion* (CHURCH), 359-363.
Cherokee limestone, Missouri: character and composition, 334.
Chile: copper-deposits, 130.
Chimney-deposits: definition, 58.
examples, 58.
China: gold-quartz veins, 282.
Chloride ores: distribution, [768].
occurrence, 136.
Chlorides: copper: effect in solution of gold, 773, 781.
in mine-waters, 766.
Chlorine: agency in transportation of metals, 722.
amount necessary for solution of gold in presence of manganese compounds, 784.
distribution, 767.
in igneous rocks, 751.
in mine-waters, 766, 779.
in natural waters: map, New England and New York, 769.
in volcanic emanations, 723.
nascent: agency in solution of gold, 777.
quantity in igneous rocks, 734.
solvent of gold, 174.
with manganese compounds: solubility of gold in, 784.
Christiania region, Norway: igneous rocks: classification, 692.
Christmas mine, Cripple Creek, Colo., 422.
Christy, S. B.: bitumen associated with quicksilver, 345.
Chromium: distribution in igneous rocks, 750.
in basic rocks, 285.
in igneous rocks, 267.
quantity in igneous rocks, 733.
CHURCH, JOHN A.: *Discussion on Geological Distribution of Useful Metals in the United States*, 83-86.
Discussion on The Chemistry of Ore-Deposition, 359-363.
deposition of ores in limestone, 341.
Circulation: meteoric waters, 242, 243.
ore-bearing solutions: factors controlling, 791.
Clarke, F. W.: average composition of igneous rocks, [734].
chlorine-content of igneous rocks, [767].

Clarke, F. W.: formula of vesuvianite, [572].
manganese in igneous rocks, [794].
reactions produced by hot waters, [726].
relative proportion of elements in earth's crust, [293].
rock-analyses, [767], [794].
Classification: Algonkian rocks, 69.
genetic: Clifton-Morenci ore-deposits, 556.
ore-deposits, 286, 366.
products of alteration, 123.
rock-fractures, 40.
Cleavage-planes: cause, 41.
definition, 101.
CLERC, F. L.: *The Ore-Deposits of the Joplin Region, Missouri* [*Trans.*, xxxviii, 320-343], *Notice*, 833-834.
Clifton-Morenci district, Arizona: depth of oxidized zone, 545.
distribution of ores, 540.
fluid inclusions, 545.
genesis of ores, 551.
genetic classification of deposits, 556.
geology, 519.
groundwater conditions, 544.
Climatic conditions: effect on alteration, 120.
Coal, bituminous: association with ore-deposits, 320.
Coast-sediments: examination for gold, 196.
Cobalt: in igneous rocks, 269, 752.
in Sudbury pyrrhotites, 466.
presence in pyrrhotite, 461.
quantity in igneous rocks, 733.
Colorado: Cripple Creek district: ore-deposits, 411.
gold-production, 437, 441.
pre-Mesozoic gold-deposits, 447.
relation of rain-fall, run off, and evaporation, 698.
Rico: mineral veins, 226.
San Juan region: vein-system, 290.
Colorados (gossan): definition, 112.
Comagmatic region: definition, 738.
Comb-structure: veins, 10.
Compression-fissures: Butte, Mont., 55.
Compression-fractures: characteristics, 45.
Compression-joints: definition, 41, 50.
Comstock, T. B.: genesis of Red Mountain deposits, 31.
The Geology and Vein-Structure of Southwestern Colorado, [31].
vein-system of San Juan region, Colo., 290.
Comstock district: comparison with Tonopah, Nev., 601.
Comstock lode, Nevada: genesis of ores, ix, x, 19, 85, 803.
gold-production, 440.
production of silver and gold, and relation of ores, 801, 802.
structural features, 60.
Comstock vein: extent, 11.
structure, 10.
Concentration: gold: in oxidized zone, 797.
iron-deposits: Lake Superior, 125.
natural: minerals, 255.
ore-metals, 300.
Concentration-process: ore-deposits, 29.
Consanguinity: in rocks, 738.
Contact-deposits: character and genesis, xix.
examples, 38.
formation, 230.
miners' use of term, 37.
Contact-metamorphic deposits, 432.
distribution, 396.
genesis, 387, 392.
geographic distribution, 373.
Contact-metamorphic effects: variability, 578.
Contact-metamorphic ore-deposits: character, 371.
Contact-metamorphic zones, 371.
Contact-metamorphism: Baunack, Mont., 382.
Clifton-Morenci district, Arizona, 522.
effects, 385.
Elkhorn district, Montana, 576.
hydrothermal, 529.
origin, 262.
San Jose, Tamaulipas, Mexico, 567.
western Nevada, 617.
Contact-planes: definition, 37.
Contour-mapping: introduction, xxxii.
Contraction hypothesis, 42.
Contraction-planes: origin and extent, 35.
relation to ore-deposition, 35.
Copper: deposition from sea-water, 258.
distribution in igneous rocks, 752.
in basic rocks, 285.
in igneous rocks, 270.
in mine-waters, 770, 781.
in nature: detection, 77.
quantity in igneous rocks, 733.
reducing power, 358.
Copper chlorides: effect on solubility of gold, 773, 781.
Copper Cliff mine, Sudbury, Ontario, 456, 501.
photomicrographs of ore, 489, 491.
Copper-deposits: alteration, 114, 128-131.
Appalachians: genesis, 76.
Arizona: Bisbee, 829.
Clifton, 401.
Clifton-Morenci (LINDGREN), xxv, 517-556.
classification, 521.
climatic effects, 122.
Jerome, 136.
superficial alteration, 128.
Australia: Chillagoe district, North Queensland, 830.
Cananea type, 374.
Chile, 130.
climatic effects, 122.
Colorado: Evergreen, 835.
concentration, 76.
genesis, 75-77.
Idaho: Mackay, 833.
kind of rock in which found, 77.
Lake Superior district, 76.
Mansfeld, Harz mountains, 36.
Mexico: Cananea, 396.
Michigan: climatic effects, 121.
Montana: Butte City: alteration, 130.
genesis, 76.
San Jose, Tamaulipas, Mexico (KEMP), xxv-xxvi, 557-581.
source of material, 75.

Copper-deposits: Tasmania: climatic effects, 122.
Tennessee: Ducktown: alteration, 130.
Copper-iron sulphides: secondary enrichment, 832.
Copper-veins: Butte, Mont., 224, 225, 403.
Virgilina, Va., 220.
Coriolanus mine, Cripple Creek, Colo., 419.
Cornwall, England: veins: structure, 10, 225.
Coronadite, Clifton-Morenci district, Arizona, 519.
Coronado lode, Clifton-Morenci district, Arizona, 543.
Coronado quartzite, Clifton-Morenci district, Arizona, 519.
Correlation of the elements, 743.
Correlation table: pre-Cambrian series of the Lake Superior region, 634.
Cotta, B.: derivation of vein-materials, 22.
Treatise on Ore-Deposits, [viii], 316.
Country-rock: auriferous lodes: examination, 183.
Colorado: Custer county: assays for silver, 161.
Leadville: investigations, 23.
Silver Cliff: assays for silver, 161.
investigations, 23.
Ten-Mile: investigations, 23.
Influence on Mineral Veins (WEED), 216–234.
influence on vein-filling, 222, 223.
Nevada: Washoe: investigations, 23.
New Zealand: classes, 212.
of ore-deposits: decay, 117.
sheeting, 46, 47.
vadose region of Walhalla gold-field, Victoria, 186.
Covellite: reducing power, 358.
Cracks: in glass: produced by torsional strain, 51.
Creighton mine, Sudbury, Ontario, 502.
photomicrographs of ore, 490–492.
Cretaceous gold-deposits, 435–438.
Cretaceous rocks, Tamaulipas, Mexico, 561.
Cripple Creek and Silver Cliff ore-deposits compared, 158.
Cripple Creek district, Colorado: gold-production, 441.
ore-deposits, 411, 819.
rocks, 718.
underground-water conditions, 699.
CROSBY, W. O.: *Ore-Deposits of the Eastern Gold-Belt of North Carolina* [*Trans.*, xxxviii, 849–856], *Notice*, 834–835.
origin of cross-joints, 44.
torsional hypothesis, [95].
Crosby and Fuller: origin of pegmatite, 275.
Cross, Whitman: absence of steam in Kilauea, 390.
Democrat and Ben Eaton mines, Colo., [157].
Cross-joints: definition, 40.
origin, 44.
Crown Point-Belcher bonanza, 361.
Crowning Glory gold-mine, Silver Peak, Nev., 621, [813].
cross-section, 625.
Crushed zones: ore-deposits, 57.
Crystalline rocks: see Rocks.
Crystallization: in igneous rocks: order, 261, 263.
in magmas: order, 585.
Cupric chlorides: see Chlorides, copper.
Cupric salts: efficiency in promoting solution of gold, 782.
Curtis, J. S.: ore-deposits of Eureka district, Nev., 7, 58.
Curve: gold in vadose country-rock, Walhalla, Victoria, 192.
Custer county: country-rock: assays, 161.

Dacite: Tonopah, Nev., 593.
Dacite-porphyry: percentage composition, 565.
DAGGETT, ELLSWORTH: *The Extraordinary Faulting at the Berlin mine, Nevada* [*Trans.*, xxxviii, 297–309], *Notice*, 833.
Daintree, Richard: auriferous rocks of Queensland, 282.
Dannemora mine, Sweden: diagram, 661.
Dart River: auriferous lode, North Gippsland, Victoria: assays, 184.
Daubrée, A.: classification of rock fractures, 40.
experiments on glass, 51.
genesis of titaniferous albite veins, 587.
movement in rocks, 92, 93, 94.
production of joints, 94.
subterranean waters, 29.
synthetic experiments, [2].
torsion experiments on glass plates, 95.
Dawson, G. M.: quartz-veins associated with granite, 279.
Dead Pine mine, Cripple Creek, Colo., 419.
Deadwood mine, Cripple Creek, Colo., 422.
Death valley: borax-deposits, [835].
Decomposition of volcanic rocks, 727.
Deep mines: dryness, 241.
Deformation: modes, 92.
DE KALB, COURTENAY: *Geology of the Exposed Treasure Lode, Mojave, California* [*Trans.*, xxxvii, 310–319], *Notice*, 834.
gold-deposits of Exposed Treasure mine, Cal., 824.
De la Beche: mineral veins of Cornwall, 226.
mineral veins of Derbyshire, 229.
vein-formation, 220.
Delamar district, Idaho: comparison with Tonopah, Nev., 601.
Delamar gold-mine, Nevada, [794], [828].
De Launay, L.: distribution of rare elements, 745.
genesis of iron-ores, 678.
genesis of ore-deposits, [253].
Del Mar, Alexander: gold-resources of the world, 425.
Delmonico mine, Cripple Creek, Colo., 422.
Democrat mine, Silver Cliff region, Colo., 157.
Depth of alteration of ore-deposits in unglaciated regions, 122.
Derby, O. A.: Brazilian gold-veins, [239].
Derbyshire lead-mines, 229.
Descending solutions: agency at Leadville, Colo., 12.
Descending waters: agency in formation of iron-deposits, 69–71.
Detection and Estimation of Small Quantities of Gold and Silver (WAGONER), 829.

Deville, C. St. C.: juvenile waters, [xxxvii].
volcanic gases, 723.
Diaclase: rocks, 92.
Diaclases: definition, 40.
Diamond swindle: Vermilion Creek Basin, Wyoming, [xxxiii].
DICKSON, C. W.: *The Ore-Deposits of Sudbury, Ontario*, xxiv-xxv, 455-516.
Differentiation: igneous magmas, 67.
Dikes (see also Intrusions): Forty-Mile district, Alaska, 272.
San Jose, Tamaulipas, Mexico, 565.
Dillon mine, Cripple Creek, Colo., 419.
Diopside: San Jose, Tamaulipas, Mexico, 570.
Diorite: source of nickel-ores, 90.
Diorite-porphyry: San Jose, Tamaulipas, Mexico, 563.
Distribution of the Elements in Igneous Rocks (WASHINGTON), xxviii, 729-758.
"Distributive" faults, 221.
Doctor-Jack Pot mine, Cripple Creek, Colo., 423.
Doelter: preparation of pyrrhotite, 460.
Dolcoath mine, Cornwall, 225.
Dolcoath mine, Montana, [383].
Dolomite: disintegration, 336.
unaltered: distribution on Fryer hill, Leadville, Colo., 13.
DON, JOHN R.: *The Genesis of Certain Auriferous Lodes*, xvi, 162-215; *Discussion* (LE CONTE), 202; (EMMONS), 202-206; (BECKER), 207-208; (WINSLOW), 208-211; (BLAKE), 211-212; (DON), 212-215.
analyses of Australian mine-waters, [779].
chlorine as solvent of gold, 763.
genesis of auriferous lodes, 696.
method of determining gold in sea-water, 194.
solution of gold, 763, 771, 773.
Douglas, James: secondary enrichment, xli.
Drinkwater mine, Silver Peak, Nev., 621.
cross-section, 625.
Dryness of deep mines, 241, 698.
Ducktown, Tenn., copper-deposits, 510.
alteration, 130.
Dunderland, Norway, iron-ores, 690.
Dustiness of mines: explanation, 698.
Duty of a reducing agent: definition, 347.
Dynamic disturbance of earth's crust: periodicity, 43.
Dynamic movements: effect on water-channels, 34.

Eakins, L. G.: assays for silver, 161.
Earthquakes: relation to rock-flowage, 712.
theory, 44.
Earth's axis: shifting as explanation of stress, 715.
East Tennessee mine: photomicrographs of ore, 494.
Edgemont, Nev., gold-deposits, 815.
Edison, T. A.: magnetic separation of nickel-ores, 467.
Egleston, T.: petroleum associated with quicksilver, 344.
Eisener Hut (gossan): definition, 112.
Elba Island: iron-ores, 8-9.
Elements: correlation, 743.
distribution in igneous rocks, 754.
rare: distribution, 745.
Elenita mine, Cananea, Mexico, 398.
Elisa mine, Cananea, Mexico, 398.
Elk mountains, Gunnison county, Colo.: fissure-faulting, 49.
Elkhorn district, Montana: ore-deposits, 382.
Elkton mine, Cripple Creek, Colo., 420.
Ellis, H. R.: coal carrying gold, 321.
Elsie mine, Snider township, Sudbury district, Ontario, 500.
photomicrographs of ore, 489-490.
Emma mine, Tintic district, Utah, 362.
Emmens, S. H.: nickel-minerals from Sudbury, 457.
EMMONS, SAMUEL FRANKLIN: *Biographical Notice* (BECKER), xxxi-xlix.
List of Scientific Publications, xliv-xlix.
Introduction, vii-xxviii.
The Genesis of Certain Ore-Deposits, xi, 1-25.
Geological Distribution of the Useful Metals in the United States, xii, 65-83; *Discussion* (CHURCH), 83-86; (WINSLOW), 86-89; (EMMONS), 89-90; (MERRITT), 90-91.
Some Mines of Rosita and Silver Cliff, Colorado, xvi, 139-161.
Structural Relations of Ore-Deposits [*Trans.*, xvi, 804], xii, 26-64.
Discussion on The Genesis of Certain Auriferous Lodes, 202-206.
association of gold with manganese, [787].
chlorine in natural water, 768.
copper-deposits of Boundary district, British Columbia, 374, 375.
Delamar mine, Nev., 828.
genesis of certain ore-deposits, [27].
genesis of Leadville ore-deposits, xxxvi.
gold-deposits of Black Hills, [811].
increase in production of gold, 425.
investigations of country-rocks, Leadville, 23.
manganese as indication of rich ore, 787.
manganiferous gold-ore, Leadville, Colo., 816.
manganiferous silver-ore at Leadville, Colo., 800.
non-mineral-bearing fissures, Leadville, Colo., 49.
origin of Sudbury nickel-ores, 486.
secondary enrichment of ore-deposits, [696], [761], [811].
silver-ores of Aspen, Colo., 332.
Theories of Ore-Deposition Historically Considered, [viii].
veins of Butte, Mont., 55.
Emmons, S. F., and Irving, J. D.: Downtown District, xxxviii.
Emmons, Irving, and Jaggar: gold-deposits, Black Hills, S. D., [810].
EMMONS, W. H.: *The Agency of Manganese in the Superficial Alteration and Secondary Enrichment of Gold-Deposits in the United States*, xxviii, 759-828.
gold-deposits, Edgemont, Nev., [815].
Midas, Gold Circle district, Nev., [827].

Emmons, W. H., and Garrey, G. H.: gold-deposits, Manhattan, Nev., [827].
Enargite: in Butte, Mont., ore-deposits, 403.
reducing power, 354, 358.
Enrichment of ore-deposits: see Ore-deposits.
Enrichment theory, 408.
Eruptions: ejecting metalliferous magmas, 716.
kinds of magmas ejected, 715.
of igneous material; source, 43.
Eruptive activity: association with ore-deposition, 21.
Eruptive rocks: see Rocks.
Eruptive theory: ore-deposits, 8.
Erzgebirge, Freiberg, Saxony: vein-system, 52.
Eureka district, Nev.: ore-deposits, 58.
genesis, 7.
Evergreen Copper-Deposits, Colorado (RITTER), 835.
Exposed Treasure lode, Mojave, Cal.: geology, 834.
gold-deposits, 823.
relations of ores, 804.
Extraordinary Faulting at the Berlin mine, Nevada (DAGGETT), 833.

Fahlcrantz, A. E.: iron-ores, Sweden, 666.
Faltenverwerfungen (fold-faults): definition, 41.
Faulting (see also Fissures): character of movement, 102.
determined by stresses, 104.
horizontal: Mt. Guyot, Colo., 64.
illustrated by torsion experiments, 99.
in Cambrian rocks of Missouri, 88.
in Mississippian rocks of Missouri: absence, 88.
Leadville, Colo., [3].
Nevada, Berlin mine, 833.
Ontario mine, Utah, 62.
Queen of the West mine, Colo., 62–64.
Fault-fissure deposits: Ontario mine, Utah, 60.
Fault-planes: effect on water-channels, 34.
Leadville, Colo.: lack of ore-deposits, 10.
Faults (see also Fissures and Fold-faults): extent, 39.
lack of uniformity in nomenclature, 40.
FAY, A. H.: *Geology and Mining of the Tin-Deposits of Cape Prince of Wales, Alaska* [*Trans.*, xxxviii, 664–682], *Notice*, 833.
Features of the Occurrence of Ore at Red Mountain, Ouray County, Colo. (SCHWARZ), 831.
FERGUSON, H. G., IRVING, J. D., SMITH, H. D.: *Bibliography of the Science of Ore-Deposits*, 837–928.
Ferric chloride: solvent of gold, 173.
Ferric salts: efficiency in solution of gold, 781.
Ferric sulphate: solvent of gold, 173.
Ferrous sulphate: precipitant of gold, 784.
reducing power, 355, 356, 358.
Filter for sea-water in testing for gold, 198.
Finlay, G. I.: analysis of analcite-tinguaite, 566.
analysis of basalt, 567.
analysis of camptonite, 566.
Finlay, G. I.: analysis of diorite-porphyry, 564.
eruptive rocks of San Carlos range, Mexico, 558.
Finlay, J. R.: analyses of gabbro, 563.
Fissure-faults: definition, 41.
examples: Gunnison county, Colo., 49.
San Juan region, Colo., 50.
Fissure-planes: repeated movements, 59.
Fissure-systems:
Clifton-Morenci district, Arizona, 539.
Conrad Hill, Davidson county, N. C.: character and origin, 103.
origin, 60.
simultaneous production, 104.
Fissure-veins: extent in depth, 11.
gold-bearing, 427.
relations of length and depth, 11.
so-called: formation, 10.
walls, 54.
Fissures (see also faults):
conducting ore-bearing solutions, 700.
extent, 53.
limiting depth, 44.
relation of walls, 713.
structural features characterizing, 45.
Fissuring: relation to ore-bodies, 339.
Flowage-zone: effect on open channels, 699.
Fluid-inclusions: Clifton-Morenci district, Arizona, 545.
Fluorine: distribution in igneous rocks, 751.
Fold-fault: definition, 41.
examples, Leadville, Colo., 48.
typical form: origin, 47.
Foliation-planes: cause, 41.
Forchhammer: metals in ashes of marine plants, [256].
Formation and Enrichment of Ore-Bearing Veins (BANCROFT), 696–719; *Supplementary Paper* (BANCROFT), 720–728.
Formulæ for reducing power of minerals, 348.
Fossil remains: replaced by ore, 87.
Foster, C. Le Neve: veins of Cornwall, 10.
Fouqué, F. A.: volcanic gases, 388.
Fracture: causes, 41.
copper-steel: character, 101.
Fracture-system: Ontario mine, Utah, 61.
Free Coinage mine, Cripple Creek, Colo., 422.
Freeland, F. T.: sulphide ores, Leadville, Colo., 3.
Freiberg, Saxony: vein-system, 52.
Frood mine, McKim township, Sudbury district, Ontario, 500.
Fryer hill, Leadville, Colo.: ore-deposits, 13.
Fumaroles: gases from, 389.
sublimation products: composition, 390.
Fumarolic deposits, 368.
Fumarolic origin of ore-deposits, 240.
Furnace canyon: borax deposits, [835].
Furstenburg: Wenzal vein: varying with country-rock, 227.
Fusion, region of: depth, 22.

Gabbro: Tamaulipas, Mexico, 563.
Galena: effect of pyrite on solubility, [766].
occurrence in shale, Missouri, 330.
reducing power, 358.

Garnet: San Jose, Tamaulipas, Mexico, 570.
Garnet-Formations of Chillagoe Copper Field, North Queensland, Australia (SMITH), 830.
Garrey, Ball, and Spurr: silver-lead deposits of Georgetown and Silver Plume, Colo., [816].
Garrey, Emmons, and Ransome: gold-deposits, Bullfrog district, Nev., [827].
Garrey, G. H., and Emmons, W. H.: gold-deposits, Manhattan, Nev., [827].
Garrey, G. H., and Spurr, J. E.: ore-deposits of Georgetown, Colo., [816], [817].
Gas-content of rocks, 767.
Gautier, Armand: gases occluded in rocks, [390], [767].
Geikie, A.: origin of igneous rocks, [260].
volcanic gases, 388.
Gellivare iron-deposits, Norrbotten, Sweden, 671.
Genesis: *Auriferous Lodes* (DON), xvi, 162-215.
copper-deposits, 75-77.
gold- and silver-deposits, 80-81.
iron-deposits, 69-71.
Lake Valley, New Mexico, Silver-Deposits, (KEYES), 835.
lead- and zinc-deposits, 77-79.
manganese-deposits, 74-75.
nickel deposits, 75.
Ore-Deposits (EMMONS), xi, 1-25.
Ore-Deposits at Bingham, Utah (BOUTWELL), 831.
quicksilver-deposits, 79.
Sudbury, Ontario, nickel-ores, 477.
Tonopah ores, 598.
Genetic Relations of the Western Nevada Ores (SPURR), xxvi, 590-620.
Geologic history: California region, 583.
Geological Distribution of the Useful Metals in the United States (EMMONS), xii, 65-83, 89-90; *Discussion*, 83-91.
Geological maps:
central Sweden, 658.
Lake Superior region, 636.
Norrbotten, Sweden, ore-province, 673.
San Jose district, Tamaulipas, Mexico, 560.
Geology and Copper-Deposits of Bisbee, Arizona (RANSOME), 829.
Geology and Mining of the Tin-Deposits of Cape Prince of Wales, Alaska (FAY), 833.
Geology and Petrography of the Goldfield Mining-District, Nevada (HASTINGS and BERKEY), 832.
Geology: Clifton-Morenci district, Arizona, 518.
Exposed Treasure Lode, Mojave, California (DE KALB), 834.
Lake Superior iron-bearing and copper-bearing series, 633.
Rossland, B. C., pyrrhotite-deposits, 48.
South Island, New Zealand, 162.
Sudbury, Ontario, nickel-deposits, 479, 481.
Treadwell Ore-Deposits, Douglas Island, Alaska (SPENCER), 830.
Virginia Barite-Deposits (WATSON), 834.
Georgetown, Colo.: silver-lead deposits, 816.
Georgetown quadrangle, Colo.: gold-deposits, 817.
Gertrude mine, Creighton township, Sudbury district, Ontario, 504.
photomicrographs of ore, 491-492.
Geyser: definition, 32.
Geyser shaft: Silver Cliff, Colo.: section, 144.
Geyser gold-mine, Silver Cliff, Colo., xvi.
analyses of ore, 147.
analyses of water, 151, 152.
country-rocks, 143.
deep deposits, 142.
exploration-work, 143.
nitrate-content of waters, 768, 778.
ore-bodies, 145.
vein-materials, 146.
water-courses, 147.
Gilbert, G. K.: temperature of thermal waters, 245.
GILLETTE, H. P.: *Osmosis as a Factor in Ore-Formation*, xxiv, 450-454.
Glaciation: control of depth of alteration, 121.
Glaciers in the United States: first discovery, xxxi.
Glass cracked by torsional strain, 51.
Glass plates: torsional experiments, 95.
Godiva mountain ore-bearing beds, 338.
Gogebic district: locus of ore-deposits, 646.
Gold: allotropic forms: behavior with mercury, 107.
conditions producing, 108.
conversion to ordinary form, 108.
Allotropism (LOUIS), 105-109.
amalgamation, 107.
association: with carbonaceous slates in California, 211.
with coal, 321.
with manganese oxides, 786.
with platinum in Urals, 289.
with pyrites, 132.
with sulphides, 203.
chemical properties, 107.
concentration in oxidized zone, 797.
contact-metamorphic deposits, 432.
criteria for determining secondary origin, 792.
crystallization, 105.
deep-seated enrichment: vertical relation to chalcocitization, 798.
determination of small amounts in sea-water, 829.
difference between placer- and vein-gold, 182.
distribution in igneous rocks, 752.
experiments in solution and deposition, [763], 771.
fineness: variation, 182.
forms from precipitation, 105.
free: in undecomposed rocks, 208, 214.
general diffusion, 209.
geologic age of deposition, 429.
in assays of California rocks, 301.
in coal from Wyoming, 211.
in country-rock, 210.
in country-rock at deep levels, Walhalla, Victoria; curve, 193.
in diorite, 90.
in igneous rocks, 271.
in mine-waters: evidence for, 178.
search for, 179.

Gold: in sea-water, 191, 192.
determinations, 195.
methods of detecting, 193.
in siliceous igneous rocks, 286.
in vadose country-rock, Walhalla, Victoria: curve, 192.
mode of occurrence, 108, 724.
native: deposition by primary processes, 793.
natural solvents, 173.
occurrence in sulphides, New Zealand, 170.
origin in stratified deposits, 191.
placer-deposits, 133.
precipitation, 784.
by black shales, 331.
from sea-water, 194.
experiments, 198, 199.
in marine sediments, 196.
reagents, 108.
relative fineness of vadose and deep vein-gold, 184.
"rustiness," 109.
solution: reactions, 777.
and re-precipitation, 206.
in vadose waters, 177.
source, 201.
in pyrite, 203.
specific gravities, 106.
tests for: in rocks at Leadville, Colo., 16.
transfer in cold solutions, 785.
varieties, 105.
Witwatersrand, Transvaal: action with reagents, 109.
Gold Circle, Nev.: gold-deposits, 827.
Gold Coin gold-mine, Cripple Creek, Colo., 419, [821].
Gold-concentrations: occurrence, 271.
Gold-content of sea-water: amount, 206.
Gold-deposits (see also Gold-silver deposits):
Agency of Manganese in Alteration and Enrichment, 759-828.
Alabama, [810].
Alaska: Berner's Bay, 811.
Treadwell mines, 811.
alteration, 132-133.
Appalachian, 806.
association with eruptive rocks, 80.
Bannack type, 381.
California, Bodie, 823.
Mojave: Exposed Treasure mine, 823.
Mother Lode district, 811, 830.
Nevada City and Grass Valley district, 812.
Ophir district, 813.
classification according to age, 433.
classification (Lindgren's), [763], [806].
Colorado: Cripple Creek, 159, 819.
Georgetown quadrangle, 817.
Leadville, 815.
Mt. Guyot, near Breckenridge, 64.
San Juan, 818.
Summit district, 822.
concentration, 80.
in oxidized zone, 797.
Cretaceous, 435, 806.
formation, 172.
greater richness in vadose region, 171.
Homestake type in South Dakota, 806.
Idaho, [815].
Gold-deposits: Montana, Granite mountain, 122.
other districts, 815.
Philipsburg, [762], 814.
Nevada: Bullfrog district, 827.
Delamar mine, 828.
Edgemont, 815.
Gold Circle district, 827.
Goldfield, 825.
Manhattan, 826.
Silver Peak, 813.
Tonopah, 68.
Ontario, 445.
Pre-Cambrian, 434.
South Carolina: Haile mine, 806.
South Dakota: Black Hills, 810.
Southern Appalachian districts, 809.
Tertiary, 807.
United States: superficial alteration and secondary enrichment by agency of manganese, 759.
Utah: Annie Laurie mine, 827.
Golden Cycle mine, Cripple Creek, Colo., 422.
Goldfield district, Nevada: geology and ore-deposits, 599.
geology and petrography, 832.
gold-deposits, 825.
Gold Ledge, Mercur, Utah: origin, 290.
Gold-mine waters: salts in, 764.
Gold-mines (see also Gold-silver mines):
Alaska: Treadwell, Douglas Island, 811.
California: Exposed Treasure, Mojave, 804, 823.
Colorado: Camp Bird, Ouray, [787], [818].
Geyser, Silver Cliff, [766].
Gold Coin, Cripple Creek, [821]
Pharmacist, Cripple Creek, [819].
Summit, Cripple Creek, [819].
Tomboy, Silverton, [787], [818].
Montana: Cable, Philipsburg, [762], [814].
Granite-Bimetallic, Philipsburg, [762], [814].
Nevada: Crowning Glory, Silver Peak, [813].
Delamar, [794], [828].
Drinkwater, Silver Peak, [813].
South Carolina: Haile, [794], [810].
Utah: Annie Laurie, [827].
Gold Mountain, Nev.: geology and ore-deposits, 599.
Gold-ores: in contact-deposits, 380.
Gold-production: future status, 442, 445.
increase: causes, 442.
North America, 442-444.
The Geological Features: (LINDGREN), xxiii-xxiv, 424-444.
Tertiary deposits, 438.
unit of measurement, 433.
Victoria, 171.
Gold-provinces of the United States, 806.
Gold-quartz veins: connection with basic igneous rocks, 284.
genetic connection with siliceous igneous rocks, 279.
Gold-silver and silver-gold ores: vertical relations, in deposits, 799.
Gold-silver deposits:
California: Bodie, 823.
Mojave, 823.
Ophir district, 813.

Gold-silver deposits Montana: Philipsburg, [762], [814].
Nevada: Gold Hill group, Comstock lode, [804.]
Gold-silver mines (see also Silver-gold mines):
Nevada: Gold Hill group, Comstock lode, [804].
Yellow Jacket, Comstock lode, [804].
Gonzalo, Joaquin: copper-deposits of Huelva, xli.
Gooch and Whitfield: arsenic in hot-springs waters, [404].
Gossan: appearance, 112.
definition, 112.
Gossan-ores: Appalachians, 73.
Gottlob vein, Freiberg, Saxony, 218.
Gottschalk and Buehler: effect of pyrite on solubility of galena, [766].
Grabill, L. R.: charcoal in the Bassick mine, 319.
Grand Central mine, Tintic district, Utah, 335, 337.
Grängesberg, Sweden: map, 662.
Grängesberg iron-deposits, Sweden, 671.
Granite: New Zealand: samples for analysis, 163.
solution by acids, 726.
Granite-Bimetallic gold-mine: Philipsburg quadrangle, Mont., 814.
Granite-Bimetallic lode: Philipsburg quadrangle, Mont.: character of gold-enrichment, 762.
Granite mine, Cripple Creek, Colo., 419.
Granite Mountain, Montana, gold-deposits: depth of alteration, 122.
Granitic rocks: origin, 608.
Graphite: occurrence. 315.
Grärberg mines, Sweden: origin of iron-ores, 670.
Grass Valley, Cal.: gold-deposits, 812.
Graton, L. C.: enrichment of gold-deposits, Haile mine, S. C., [810].
gold-deposits of central and southern North Carolina, [835].
minerals in Appalachian gold-deposits, 809.
Gravity: influence in magmatic differentiation, 72.
Great Gulch ores: genetic relations, 612.
Groddeck, A. von: nature of veins. 26.
Kristiania type of contact-deposits, 372.
ores in sedimentary rocks, 256.
replacement ores, xxxix.
Grossularite: San Jose, Tamaulipas, Mexico, 572.
Ground-water: in mines, 248.
in lithosphere, 698.
Guadalupe mine, Chihuahua, Mex.: vein-formation, 218.
Gunnison region, Colo.: bog-iron deposits, 32.
walls of fissure-veins, 55.
GUNTHER, C. G., and KEMP, J. F.: *The White Knob Copper-Deposits, Mackay, Idaho* [*Trans.*, xxxviii, 269-296], *Notice*, 833.
Gympie, Queensland: rocks, 163.
Gypsum-deposits: alteration, 114.
expansion in formation, 116.
formation, 116.
Habermehl: composition of pyrrhotite, 459.
Hague and King: genesis of Comstock lode, x.
Haile gold-mine, South Carolina, [794], [806], [810].
Hall, C. W.: origin of pegmatite, 275.
Hallowell, J. K.: ore-deposits in Gunnison region, Colo., 32.
Halogens: agency in transferring metals, 728.
Haloid compounds in ore-deposits: formation in arid regions, 135.
Harker, Albert: average composition of igneous rocks, [734].
contact-effects in Westmoreland, 575.
HASTINGS, J. B.: *Are the Quartz-Veins of Silver Peak, Nevada, the Result of Magmatic Segregation?*, xxvi, 621-628.
HASTINGS, J. B., and BERKEY, C. P.: *The Geology and Petrography of the Goldfield Mining-District, Nevada* [*Trans.*, xxxvii, 140-159], *Notice*, 832.
Hausmann: iron-ores of Taberg, Småland, 681.
Hawes: contact-metamorphic phenomena, 525.
Headden, W. P.: deposition of basic sulphate, 710.
Heat: rôle in ore-deposition, 2.
Heim, A.: classification of rock-fractures, 41.
limiting depth of fissures, 44.
Hematite: Grant county, N. M.: origin, 127.
transformation to and from magnetite, 670, 671.
Henrich, F.: decomposition of volcanic rocks, 727.
Hill, R. T.: Cretaceous rocks of Tamaulipas, Mexico, 561.
origin of Mexican iron-deposits, 127.
Hillebrand, W. F.: analyses: sinters, 149.
water from Geyser mine, 151, 152.
elements in igneous rocks, 732.
Hills, R. C.: formation of ore-deposits, [233].
gold-deposits, Summit district, Colo., 822.
Hillside mine, Cripple Creek, Colo., 420.
Hinge-faults: definition, 103.
Hoefer: ores in sedimentary rocks, 256.
Hoefer's Method of Determining Faults in Mineral Veins, [101].
Högbom: iron-ores of Norrbotten, Sweden, 678, 679.
Högborn mines, Sweden: plan, 668.
Horn-silver: in Exposed Treasure mine, Mojave, Cal., [804].
in mines on Comstock lode, Nev., [804].
theories of formation, 800.
Hornblende: in rocks of New Zealand, Victoria, and Queensland: analyses, 167-168.
separation from augite, 166.
separation from rocks for examination, 165.
separation from syenite, 165.
Hot springs: decrease in flow, 704.
explanation, 597.
HOWE, H. M.: *Discussion on The Torsional Theory of Joints*, 101.

Huanatajayite: occurrence, 136.
Humboldt mine, Rosita, Colo.: locus of ore-bodies, 24.
Humus acid: reducing power, 351, 357.
Hunt, T. S.: classification of crystalline rocks, 68.
Huronian rocks: Lake Superior region, 69.
Hussak, E.: auriferous quartz-vein in Brazil, 276.
Hutton, F. W.: geology of Otago, New Zealand, [162].
source of ore-materials of Thames district, N. Z., 164.
Hydration, depth of, 119.
Hydrocarbons: classification, 308.
protective action, 311.
reducing action, 305.
Hydrogen: reducing power, 307.
Hydrothermal metamorphism, 529.

Idaho: gold-production, 437, 440.
Iddings, J. P.: consanguinity of rocks, 738.
contact metamorphic effects, 384.
formation of veins, [394].
origin of igneous rocks, 261.
Igneous activity: periods, 429.
Igneous contacts: relation to ore-deposition, 365.
Igneous rocks (see also Rocks):
Igneous Rocks and Circulating Waters as Factors in Ore-Deposition (KEMP), xxi–xxii, 235–250.
Segregation or Differentiation as Related to the Occurrence of Ores (SPURR), xxii, 251–303; *Discussion* (WINCHELL), 303–304.
Ilmenite: in eruptive rocks, 70.
Immortal mine, Silver Cliff, Colo., [140].
Independence mine, Cripple Creek, Colo., 419.
India: Travancore: quartz-reefs, 282.
Indian Queen mine, Birch Creek, Beaverhead county, Montana, [374].
Influence of Country Rock on Mineral Veins (WEED), xxi.
Intrusions: effects on circulating waters, 247.
effect on water-channels, 34.
Ontario mine, Utah, 60–62.
source of ore-materials, 20.
Iodine: solvent of gold, 173.
Iron: concentration, 255.
in basic rocks, 285.
in igneous rocks, 266, 267.
in mine-waters, 770, 781.
reducing power, 358.
Iron and manganese: in rocks: chemical relations, 795.
relative amounts in vadose and deep waters, 153.
Iron-deposits: alteration, 114, 124.
Appalachian region: mode of occurrence, 117.
origin, 71.
surface-action, 125–126.
bog: Colorado, 32.
conditions favoring formation, 73.
contact deposits in Christiania region, 692.
contraction in formation, 117.
Elba Island, 8–9.
Iron-deposits: eruptive-origin theory abandoned, 8.
formed by magmatic segregation in basic eruptions, 680.
genesis, 9, 69–71, 124.
keratophyre type, 672.
lake- and bog-ores, 694.
Lake Superior region, 637.
character, 647.
mode of concentration, 641.
origin and development, 29, 69–71, 124, 642, 654.
magnetic: Pennsylvania, 73.
Marquette region, Mich.: origin, 71.
Mesabi range, Minn.: origin, 125.
Missouri: genesis, 87.
Iron Mountain: 87, 126.
Pilot Knob, 87.
of metamorphosed Cambro-Silurian schists, 689.
Ovifak, Greenland, 72.
relations to eruptives, 72–73.
Scandinavian: The Geological Relations of (SJÖGREN), xxvi, 657–695.
Styria: surface-action, 126.
Sweden: central: types and origin, 659.
Norrbotten: structure, 676.
genesis, 677.
Sweden and Norway: lake region, 127.
Texas: origin, 127.
eastern: surface-alteration, 126.
titaniferous: map of distribution in Scandinavia, 682.
types: derivation, 73.
examples: 73.
Iron fault, Leadville, Colo., 48.
Iron Mountain, Mo.: ores: occurrence, 87.
Irving, J. D.: classification of Algonkian rocks, 69.
genesis of Lake Superior iron-deposits, 29.
iron ores: origin, 70.
minerals of gold-deposits, Homestake belt, Black Hills, S. D., 810.
Irving, J. D., and Emmons, S. F.: Downtown District, xxxviii.
Irving, Emmons, and Jaggar: gold-deposits, Black Hills, S. D. [810].
IRVING, J. D., SMITH, H. D., FERGUSON, H. G.: *Bibliography of the Science of Ore-Deposits*, 837–928.
Isabella mine, Cripple Creek, Colo., 422.

Jackson, D. D.: chlorine in waters, 767.
Jacque mountain, Ten-mile district, Colo.: structural features, 62.
Jaggar, Emmons, and Irving: gold-deposits, Black Hills, S. D., [810].
JENNEY, W. P.: *The Chemistry of Ore-Deposition*, xxii, 305–363.
formation of solid oxidized hydro-carbons, 308.
genesis of Missouri lead- and zinc-deposits, 78.
lead- and zinc-deposits of the Mississippi Valley, 306.
Jerome, Ariz.: copper-deposits, 136.
Jimenez copper-mine, Chihuahua, Mexico, [374].
Joass and Cameron: Sutherland gold-fields of Scotland, 281.

Joints: definition, 40, 101, 103.
ore-bearing: Silver Cliff, Colo., 141.
origin and extent, 35, 93.
phenomena, 92.
relation to ore-deposition, 35.
Torsional Theory (BECKER), 92-104.
Joplin region, Missouri: ore-deposits, 833.
Josie mine, Rossland district, B. C., 509.
Judd, J. W.: chlorine in volcanic emanations, 723.
disintegration of volcanic rocks, 727.
Judson, J. N.: magnetic separation of nickel-ores, 467.
Juvenile waters: origin, xx.

Kaolinization, depth of, 119.
Kawich district, Nevada: geology and ore-deposits, 600.
Keck, Rudolph: association of organic matter with ore-deposits, 344.
KEMP, J. F.: *Igneous Rocks and Circulating Waters as Factors in Ore-Deposition*, xxi, 235-250.
The Copper-Deposits at San Jose, Tamaulipas, Mexico, xxv-xxvi, 557-581.
Ducktown, Tenn., copper-deposits, 810.
genesis of ore-deposits, [253].
igneous rocks a source of vein-materials, 222.
metals in eruptive rocks, [707].
metals in igneous rocks, 295.
order of formation of minerals in crystalline rocks, 263.
origin of pegmatites, 276.
origin of Sudbury nickel-ores, 483.
rôle of igneous rocks, 384.
Rôle of the Igneous Rocks in the Formation of Veins, xix, 696.
secondary enrichment in copper-deposits, [761].
silica in the Sierras, 280.
Silver-Islet mine, 231.
vein-system of San Juan region, Colo., 290.
KEMP, J. F., and GUNTHER, C. G.: *The White Knob Copper-Deposits, Mackay, Idaho* [*Trans.*, xxxviii, 269-296], *Notice*, 833.
Keweenawan rocks, Lake Superior region, 69.
KEYES, C. R.: *Borax-Deposits of the United States* [*Trans.*, xl, 674-710], *Notice*, 835.
Genesis of the Lake Valley, New Mexico, Silver-Deposits [*Trans.*, xxxix, 139-169], *Notice*, 835.
chlorine in arid regions, 768.
Keystone mine, Silver Cliff, Colo., [140].
Kiirunavaara iron-ore deposits, Sweden, 672.
Kimball, J. P.: replacement of limestones by iron-ores, 70.
King, Clarence: genesis of Butte, Mont., deposits, 404.
horn-silver, 803.
manganese in Comstock lode, 802.
meridional zones of mineral-deposits, [81].
views as to genesis of ore-deposits, x.
King and Hague: genesis of Comstock lode, x.
King, William: joints, 93.
Kinta Valley, Federated Malay States: tin-deposits, 832,
Klein's solution: advantages, 166.
Klockmann: contact-metamorphic phenomena, 525, 527.
Knaffl, Ludwig: amalgamation of gold, 107.
Knopf, Adolph: gold-deposits, Berner's Bay district, Alaska, 811.
Kœnig, G. A., and Stockder, M.: occurrence of coal with silver, 321.
Kohler, E.: adsorption process, 536.
Kohlrausch: solubilities of silver-salts, 800.
Kolecki, Theodore: contour sketch-maps, [xxxii].
Kootenay volcanic group, 495.
Kristiania type of contact ore-deposits, 372.
permanence in depth, 393.

Laccolith: San Jose, Tamaulipas, Mexico, 563.
Lacroix, A.: metals in fumaroles, 721.
Lake Superior iron-ores: character, 647.
Lake Superior region: Algonkian rocks, 69.
development of rocks, 648.
geological map, 636.
iron-deposits, 69.
genesis, 29.
mode of concentration, 641.
origin and development, 642, 650, 654.
time of concentration, 649.
topographic relations, 650.
pre-Cambrian series, 634.
Lake Wakatipu, New Zealand: vadose country-rock: analyses, 189.
Lapparent, A. de: solution-theory of ore-deposition, 2.
Lassaigne: solubility of manganese, [796].
Lateral migration: manganese salts, 794.
Lateral-secretion theory: ore-genesis, xiii, 23-24, 82, 83, 160, 171, 201, 204, 210, 213.
Lava: experiments on, 725.
gaseous content, 767.
Lava streams: Vesuvius: steam from, 701.
Law of areal distribution of mining-districts, 325.
Law of replacement, 9.
Lead: distribution in igneous rocks, 753.
tests for: in rocks at Leadville, Colo., 16-17.
Lead-deposits: alteration, 131.
Australia: Chillagoe district, North Queensland, 830.
Commern, Eifel district, 36.
genesis, 77-79.
source of material, 77.
Virginia-Tennessee region, 831.
Lead- and zinc-deposits: association with eruptives, 78.
Missouri: occurrence in Carboniferous rocks, 88.
occurrence in Franklin county, 89.
Missouri region: genesis, 78.
Virginia-Tennessee Region (WATSON), 831-832.
Lead oxides: agency in solution of gold, 780.

Leaders: definition, 51.
Leadville, Colo.: investigations of country-rocks, 23.
ore-deposits: character, 27, 38.
genesis, xi, 5.
investigation, 26.
original depth, 7.
sulphide origin, 3.
silver-, lead-, and gold-deposits, 815.
silver-lead deposits: aqueous origin, 2.
LE CONTE, JOSEPH: *Discussion on The Genesis of Certain Auriferous Lodes*, 202.
association of eruptive activity with ore-deposition, 21.
chlorine as solvent of gold, 763.
genesis of metalliferous veins, 14–15.
mis-statement of Emmons's views on Leadville ores, 4.
Ledoux, A. R.: contact-metamorphism in Boundary district, 375.
Lehner, Victor: lead oxido: effect on solubility of gold, [780].
LEITH, C. K.: *A Summary of Lake Superior Geology with Special Reference to Recent Studies of the Iron-Bearing Series*, xxvi, 633-656.
Leptoclases: definition, 40.
Levack township deposits, Sudbury district, Ontario, 507.
Levigation theory: ore-deposits, 14.
Lignite: association with ore-deposits, 322.
reducing power, 351, 357.
Limburgite: Cripple Creek district, Colo., 412.
Lime: quantity in igneous rocks, 732.
Limestone: analyses, 334, 335, 337, 338.
chlorine-content, 766.
oxidation, 535.
relation to ore-deposits, 333.
San Jose, Tamaulipas, Mexico, 568.
Limonite: eastern Texas: origin, 126.
Limonites: origin, 124
LINCOLN, F. C.: *The Promontorio Silver-Mine, Durango, Mexico* [*Trans.*, xxxviii, 734–746], *Notice*, 834.
LINDGREN, WALDEMAR: *The Genesis of the Copper-Deposits of Clifton-Morenci, Arizona*, xxv, 517–556.
The Geological Features of the Gold-Production of North America, xxiii–xxiv, 424–444
The Occurrence of Stibnite at Steamboat Springs, Nevada, xxvi, 629–632.
andradite at Clifton-Morenci, Arizona, [572].
Annie Laurie gold-mine, Utah, 827.
auriferous quartz-vein in Brazil, 276.
Character and Genesis of Certain Contact-Deposits, [xix].
contact-deposits, 230, 237, [372].
contact-metamorphic deposits, 528.
contact metamorphism, 371.
copper-deposits, Clifton-Morenci district, Arizona, [788].
formation of metalliferous veins, 369.
garnetization at Clifton-Morenci, Ariz., 579.
genesis of ore-deposits, [253].
gold-deposits: classification, [763], 807.
Nevada City and Grass Valley, Cal., 812.
LINDGREN, WALDEMAR:
gold-deposits: Ophir district, Cal., 813.
southern Appalachians: associated minerals, [809].
hypothesis of igneous emanations, 582.
magmatic differentiation, 722.
magmatic origin of ore-deposits, 619.
metallogenetic epochs, 806.
metals in gneiss, [707].
Metasomatic Processes in Fissure-Veins, [xviii].
metasomatic replacement, [223], 225, 232.
metasomatism, xl.
osmosis in ore-formation, [xxiv].
primary pyrites, 204.
relation of ore-deposition to physical conditions, 763.
telluride ores, 380.
vein-forming waters, 586.
Lindgren, W., and Ransome, F. L.: gold-deposits, Cripple Creek, Colo., 819.
List of Scientific Publications of Samuel F. Emmons, xlii–xlvii.
Lithium: distribution in igneous rocks, 746.
quantity in igneous rocks, 734.
Lithoclases: definition, 40.
Liversidge, A.: gold in sea-water, 193.
gold in solution, 177.
origin of nuggets, [182].
Lodes: metalliferous: successive zones in depth, 789.
Löfstrad: iron-ores of Norrbotten, Sweden, 678.
Lone Mountain ores, Nevada: genetic relations, 614.
Longfellow limestone, Clifton-Morenci district, Arizona, 519, 523.
Lossen: quotation from Groddeck, 26.
Lotti, B.: studies of Elba iron-ores, 9.
LOUIS, HENRY: *The Allotropism of Gold*, xv., 105–109.
mode of occurrence of gold, 108.
ore-deposits in Permian of Nova Scotia, [327].
Lucky Guss mine, Cripple Creek, Colo., 422.
Luossavara iron-ore deposits, Sweden, 673.

McCaskey, H. D.: gold-deposits, Alabama, [810].
McCaughey, W. J.: experiments on solution of gold, 763, 771, 772, 776, 798.
McDermott, W.: association of graphite and silver in Silver-Islet mine, 317.
McLaughlin, R. P.: gold-deposits, Bodie, Cal., [823].
McTighe, T. J.: magnetic separation of nickel-ores, 467.
Macetown gold-district, N. Z.: assays, 184.
Magmas: action during cooling, 725.
differentiation phenomena, 687.
kinds ejected in eruptions, 715.
relations to ore-bodies, 717.
temperature, 724.
water in, 702.
Magmatic differentiation: ore-deposits, 67, 84, 205, 274.
Magmatic Origin of Vein-Forming Waters in Southeastern Alaska (SPENCER), xxvi, 582–589.

Magmatic segregation, 288.
as working hypothesis, 292.
effect on ore-deposits, 300.
Magmatic waters: origin, xx.
rôle, 584.
Magnesia: quantity in igneous rocks, 732.
Magnesium: in mine-waters, 768.
Magnetic iron-ore deposits, Pennsylvania, 73.
Magnetite. in eruptive rocks, 70.
in magmas, 72.
in rocks of New Zealand and Victoria: analyses, 167,
reducing power, 358.
San Jose, Tamaulipas, Mexico, 573.
transformation to and from hematite, 670, 671.
Magnetite-deposits: Colorado: genesis, 74.
Malaguti: metals in ashes of marine plants, [256].
Malaguti and Durocher: silver in sea-water, 191.
Mallet, J. W.: silver in volcanic ash, 721,
Malm, J. L.: chlorination treatment of ores, 722.
Mammoth mine, Tintic district, Utah, 335, 337.
Manganese: *Agency in Superficial Alteration and Secondary Enrichment of Gold-Deposits*, 759–828.
chemical relations with iron in rocks, 795.
chemistry of, 780.
concentration, 255.
distribution in igneous rocks, 751.
effect on solubility of gold, 778.
experiments on solution, 795.
in igneous rocks, 267.
in mine-waters, 770, 781.
occurrence in gold-deposits, 779.
quantity in igneous rocks, 733.
use in chlorination process, 762.
Manganese and iron, relative amounts in vadose and deep waters, 153.
Manganese-deposits: alteration, 127–128.
Batesville, Ark., 128.
Manganese-ore: bog: formation, 128.
southern Appalachians, 74.
Manganese oxides: association with gold-deposits, 786.
occurrence in mining-districts, 174.
reactions in dissolving gold, 778.
Manganese-salts: lateral migration from country-rock, 794.
Manganite: association with gold, 793.
Manhattan, Nev.: gold-deposits, 826.
Manipori formation, South Island, New Zealand, 162.
Map: New England and New York: normal chlorine, 769.
Marble: San Jose, Tamaulipas, Mexico, 569.
Marcasite: reducing power, 352, 357, 358.
Marquette region, Michigan: iron-deposits: origin, 71.
vertical section, 639.
Marsh-gas: association with ore-deposits, 345.
reducing power, 350, 357.
Martinique: volcanic gas: analysis, 388.
May Belle Tunnel mine, Cripple Creek, Colo., 419.
Melville, W. H.: analysis of sinter, 629.
Mendenhall, W. C.: gold in aplite dikes, Alaska, 280.
Mercury (see also Quicksilver): relations to igneous rocks, 753.
MERRITT, W. H.: *Discussion on Geological Distribution of Useful Metals in the United States*, 90–91.
origin of Sudbury nickel-ores, 483.
Mesabi ore-deposit: vertical section, 640.
Mesozoic gold-belt, 435–438.
Metalliferous lodes: successive zones in depth, 789.
Metalliferous province: definition, 293.
relation to petrographic province, 293, 297.
Metallographic province of California, 619.
Metallographic province of Nevada, 619.
Metals: distribution in sedimentary rocks, 254.
in detrital rocks, 257.
Metamorphism (see also Contact-metamorphism):
effects, 68.
hydrothermal, 529.
Sudbury district, Ontario, 514.
Metasomatic interchange: definition, 3.
Metasomatic processes, 232.
in Fissure-Veins (LINDGREN), xviii.
Metasomatic replacement: explanation, 453.
Tintic district, Utah, 342.
Metasomatism: definition, xl.
in Leadville ore-deposits, 2.
in Scandinavian iron-ores, xxvii.
Metastibnite: Steamboat Springs, Nevada, 632.
Meteoric hypothesis: inadequacy for ore-deposition on Pacific coast, 589.
Meteoric waters: circulation, 240.
rôle in formation of ore-deposits, xix.
Mexico: gold production, 435, 436, 438, 439.
Cananea copper-deposits, 376, 396.
Chihuahua: Guadalupe mine, 218.
San José: ore-deposits, 237.
Mica: in rocks of New Zealand and Victoria: analyses, 167–168.
separation from rocks for examination, 164.
Michel-Levy, A.: contact-metamorphic phenomena, 525.
Microcline: crystallization from magmas, 609.
Midget mine, Cripple Creek, Colo., 420.
Mike fault, Leadville, Colo., 48.
MILLER, W. G.: *Discussion on The Geological Features of the Gold-Production of North America*, 445–446.
Millerite: Sudbury, Ontario, 456.
Mineral-bearing currents: direction of flow, 37.
Mineral ridge, Tonopah, Nev.: mineral veins, 607.
rocks, 604.
silver-ores: genetic relations, 613.
Mineral vein: genesis, 430.
Mineral veins: *Influence of Country-Rock on* (WEED), 216–234.
near igneous contacts, 394.
Mineral zone, western America, 298.

Mineralization: due to rich solutions, 700.
of veins: rapidity, 700.
source of ores, 710.
Mineralized veins: product of expiring vulcanism, 698.
Mineralizing agents: distribution in igneous rocks, 755.
Mineralizing process: Tonopah, Nev., 594.
Mineralizing solutions: source: Tonopah, Nev., 596.
Minerals: isolated from rocks of New Zealand: analyses, 167.
isolation for examination, 164.
of secondary origin, 791.
reducing power, 347, 357.
segregation in magmas, 264.
separation from rocks by solutions, 165.
Mines (see also Gold-mines; Silver-mines, etc.):
of Rosita and Silver Cliff, Colorado (EMMONS), 139-161.
scarcity of commercially valuable, 696.
Mine-timbers: examination for gold, 180.
Mine-waters: acidity: cause, 174.
average of analyses, 765.
composition, 764.
examination: apparatus and results, 180-181.
vadose: acidity, 175.
examination for free acid and ferric salts, 176,
Mining-districts: areal distribution, 325.
review, 805.
Mint mine, Cripple Creek, Colo., 420.
Mirabel mine, Lake county, Cal.: quicksilver, 79,
Mississippi valley zinc-and lead-ores, 335.
Missouri: lead-and zinc-deposits, 327.
Sedalia: coal associated with blende, 320.
Versailles: coal associated with blende, 320.
Mitchener mine, Drury township, Sudbury district, Ontario, 505.
Mizpah silver-gold mine, Tonopah, Nev., [825].
Modoc limestone, Clifton-Morenci district, Arizona, 519, 523.
Modoc porphyry, 224.
Moissan, H.: analysis of volcanic gas, 388.
Mojave desert: borax-deposits, [835].
Mojave Mining-District, California (BATESON), 832.
Molybdenite: San Jose, Tamaulipas, Mexico, 573.
Molybdenum: distribution in igneous rocks, 750.
in siliceous rocks, 285.
Molybdenum-deposits: alteration, 135.
Mongolia: Ku Shau Tzu: ore-deposition, 359.
Montana: Bannack gold-deposits, 381.
Butte: copper-veins, 224, 225, 403.
silver-veins, 223.
vein-formation, 220.
Elkhorn district: ore-deposits, [239], 382.
gold-production, 437.
gold-quartz veins, 280.
Jefferson county: Lump Gulch silver-gold-veins: genesis, 408.
Montana: Madison county: ore-deposits produced by successive concentrations, 303-304.
mineral veins, 228-229.
Neihart: mineral veins, 227, 228.
silver-lead mines, 219.
Monument mine, Cripple Creek, Colo., 419.
Moon-Anchor mine, Cripple Creek, Colo., 420.
Moonlight mine, Cripple Creek, Colo., 420.
Morenci shale, Clifton-Morenci district, Arizona, 519, 523.
Morencite, Clifton-Morenci district, Arizona, 519.
Mosquito fault, Leadville, Colo., 48.
Mosquito range, Leadville, Colo.: faulting, 48.
uplift, 16.
Mother Lode district, Cal.: gold-deposits, 811.
Mounds: deposits from springs, 32.
Mount Guyot, near Breckenridge, Colo.: horizontal faulting, 64.
Mount Hood: ascent by Arnold Hague, [xxxi].
Mount Nickel mine, Blezard township, Sudbury district, Ontario, 497.
photomicrographs of ore, 487-488.
Mount Rainier: ascent by Emmons, [xxxi].
Mount Shasta: ascent by King and Emmons, [xxxi].
Mountain-building: periodicity, 43.
Mountain View mine, Silver Cliff, Colo., [140].
Movements: repeated: along fissure-planes, 59.
Mullan, John: Report on the Construction of a Military Road, 1863, [xxxii].
Münster: gold in sea-water, [193].
Murchison, R. I: age of auriferous rocks, 258.
horizon of gold, [ix].
Murray, A. R. F.: auriferous rocks of Victoria, 163.
Murray mine, McKim township, Sudbury district, Ontario, 500.
Muscovite: crystallization from magmas, 609.

Nason, F. L.: genesis of iron-deposits, Missouri, 87.
National mine, Cripple Creek, Colo., 420.
Natural gas: confinement, 313.
Natural water-channels: causes, 33.
Neihart, Mont.: silver-lead mines, 219.
veins, 227, 228.
Nelson granite, Rossland, B. C., 495.
Nenthorn gold-field, Otago, N. Z.: assays, 184.
Nepheline-basalt: Cripple Creek district, Colo., 411.
Nephelite-syenite: analysis, 562.
Tamaulipas, Mexico, 562.
Nevada: Belmont: dike-rocks, 277.
gold-production, 440.
metallographic province, 619.
silver-mining industry, 299.
Tonopah: geology, 591.
mineral veins, 593.
Nevada City, Cal.: gold-deposits, 812.

New Brunswick: pyrrhotite, 462.
New Mexico: San Pedro: ore-deposits, [238].
New Zealand: South Island: geology, 162.
Newberry, Cosmo: source of gold, 178.
Newberry, J. S.: age of lignitic sandstone at Silver Reef, Utah, [322].
criticism of Emmons's views answered, 4, 19.
genesis of Appalachian iron-deposits, [36]
selenium in Silver Reef, Utah, sandstones, 325.
theory of formation of solution-chambers, 6.
Newberry's theory of ore-genesis: criticism, 6, 21, 24.
Nickel: associates in rocks, 75.
distribution in igneous rocks, 751.
in basic rocks, 285, 295.
in igneous rocks, 268.
in Sudbury pyrrhotites, 466.
occurrence, 316.
quantity in igneous rocks, 733.
relation to pyrrhotite, 455, 461.
Virginia, 834.
Nickel-deposits: characteristic features, 511.
genesis, 75.
Sudbury, Ont., 90–91.
Nickel-ores: classification, 477.
concentration-experiments, 470.
Nickel Plate mine, British Columbia, 383.
Nickeliferous pyrrhotite: magnetic separation, 466.
theories of origin, 481.
Niter-deposits: formation, 115.
Nitrates: in mine-waters, 768.
reactions in dissolving gold, 776.
Norite: Sudbury, Ontario, 480.
Norrbotten, Sweden, iron-ores, 672.
Norway: island of Bömmel: igneous rocks, 281.
titaniferous iron-ore: concentration in magmas, 72.
Nova Scotia: pyrrhotite, 462.

Observations on Mother-Lode Gold-Deposits, California (PRICHARD), 830.
Occurrence of Nickel in Virginia (WATSON), 834.
Occurrence of Stibnite at Steamboat Springs, Nevada (LINDGREN), xxvi, 629–632.
Ocher-deposits: Cartersville district, Bartow county, Ga., 830.
Oddie rhyolite, Tonopah, Nev., 593.
Ohinemuri district, N. Z.: vadose country-rock: analyses, 190.
Ontario: gold-deposits, 445.
pyrrhotite, 462.
Ontario mine, Utah: structural features of deposit, 60–62.
Ophir district, Cal.: gold-deposits, 813.
Ore-bearing solutions: source, 11.
Ore-bodies: association with eruptive rocks, 697.
limited to certain magmas, 716.
mode of formation, 720.
mode of occurrence, Leadville, Colo., 13.
Queen of the West mine, Colo., 63.
relations to vein-walls: Gunnison region, Colo., 56.
Ore-currents: descent from above, 2.
Ore-deposition: aqueous solution, 29.
ascending theory, 12, 14, 15.
association with eruptive activity, 21.
by Ascending Hot Waters (WEED), xxiii, 403–410.
by thermal springs, 406.
causes, 37, 342.
character of receptacles, 30.
Chemistry, 305–363.
conditions, 24–25, 35, 37.
determining factors, 24.
differential, 362.
Igneous Rocks and Circulating Waters as Factors (KEMP), xxi, 235–250.
Ku Shau Tzu, Mongolia, 359.
lateral secretion theory, 23–24.
process, 342.
processes: western Nevada, 616.
Principles Controlling (VAN HISE), xvii.
selective hypothesis, 614.
variation in parts of an ore-body, 361.
Ore-deposits (see also names of metals):
Alaska, Treadwell, 830.
along bedding-planes, 35.
along contact-planes, 37.
along planes of rock-fracture, 39.
alteration *in situ*, 123.
ascending theory, 201.
bibliography, 837–928.
classification, 286.
climatic effects on, 120–121.
concentration, 83.
Cripple Creek District, Colorado: Basaltic Zones as Guides (STEVENS), xxiii, 411–423.
definition, 111.
depth of alteration in unglaciated regions, 122.
Eastern Gold-Belt of North Carolina (CROSBY), 834–835.
Enrichment of Gold and Silver Veins (WEED), xviii.
formation: influence of carbonaceous matter, 231.
from meteoric waters, 369.
fumarolic origin, 240.
Genesis (EMMONS), xi, 1–25, 300.
genetic classification, 366.
haloid compounds: formation in arid regions, 135.
in limestone: depth, 7.
form, 5.
Joplin Region, Missouri (CLERC), 833–834.
Kristiania type: permanence in depth, 393.
lateral-secretion theory, 82, 83, 201.
Leadville, Colo.: investigation, 26.
levigation theory, 14.
magmatic differentiation, 83.
materials: source and concentration, 159.
Montana: Butte, 55.
produced by successive concentrations, 303–304.
Near Igneous Contacts (WEED), xxiii, 364–402.
occurrence, 53.
of contact-metamorphic origin, 369.
of fumarolic origin, 368.
of gas-aqueous origin, 368.

Ore-deposits: of igneous origin, 366.
of igneous-emanation origin, 368, 370.
open-cavity theory, 4.
origin in depth, 84.
pneumatolytic origin, 240.
primary or original, 28.
receptacles: assumptions regarding, 3.
Red Mountain, Colo., 21–32.
relation to igneous rocks, 253.
relations to petrographic provinces: practical considerations, 755.
replacement theory: application, 8.
rich: factors determining location, 790.
secondary concentration: Sudbury, Ont., 90.
secondary enrichment, 761, 791, 810 *et seq.*
selective concentration, 79.
Silver Cliff, Colo.: genesis, 155.
solfataric origin, 85.
source and concentration (summary), 82.
source of materials, 15, 111.
status of investigations, 81.
Structural Relations (EMMONS), xii, 26–64.
Sudbury, Ontario (DICKSON), xxiv–xxv, 455–516.
Superficial Alteration (PENROSE), 110–138.
sulphide secondary enrichment, xvii.
Utah, Bingham, 831.
Ore-Formation: *Osmosis a Factor in* (GILLETTE), xxiv, 450–454.
Ore-genesis: ascension theory, xiii.
lateral secretion theory, xiii.
Ore-materials: migration, 123.
Ore-minerals: source in eruptive rocks, 2.
Ore-regions: association with ores of igneous activity, 253.
Ore-segregation: definition, 252.
Ore-zone: Cripple Creek, Colo.: structure, 413, 414.
Ores (see also names of metals):
deposition contemporaneous with sediments, 256.
derivation from magmas, 237.
Oregon: gold-production, 436.
Origin of Vein-filled Openings in Southeastern Alaska (SPENCER), 83.
Orphan Belle mine, Cripple Creek, Colo., 422
Osmosis as a Factor in Ore-Formation (GILLETTE), xxiv, 450–454.
Osmotic pressure: law, 451.
Osmotic separation of metal-bearing solutions, 207.
Otago, New Zealand: vadose country-rock: analyses, 188.
Otago harbor: sediments: examination for gold, 196.
Oversight mine, Cananea, Mexico, 398.
Ovifak, Greenland: iron-ore deposit, 72.
Owyhee mines, Idaho: gold-production, 440.
Oxidation: limiting depth, 118.
Oxidized ores, 581.

Pachuca district, Mexico: comparison with Tonopah, Nev., 601.
Pacos (gossan): definition, 112.
Paraclase: rocks, 92.
Paraclases: definition, 40.
Parageneses of minerals: Clifton-Morenci district, Arizona, 536.
Paris mine, Silver Peak district, Nevada, 627.
Park, James: gold in sea-water, [192].
source of ore-materials of Thames district, N. Z., 164.
Pearce, Richard: analyses of gold-ores, [820].
experiments in solution of gold, [763]. [773].
veins of Cornwall, 10.
Pearceite ores, Neihart, Montana, genesis, 404.
Pegmatite veins, 239.
Pegmatites: definition, 275.
Penfield, S. L.: pentlandite in Sudbury ores, 470.
Penokee-Gogebic ore-deposit: vertical section, 639.
PENROSE, R. A. F., JR.: *The Superficial Alteration of Ore-Deposits*, xv, 110–138, [761].
chemical relations of iron and manganese in rocks, [795].
distribution of chloride ores, [768].
fissures at Cripple Creek, Colo., 221.
formation of silver chlorides in arid countries, 801.
manganese in gold-deposits of Cripple Creek, Colo., 819.
Pentlandite: formula, 474–475.
Lillehammer, Norway, 474.
Sudbury, Ontario, 456, 474.
Permeability of rocks under heat and pressure, 29.
Persberg, Sweden: iron-deposits: map, 667.
Petrographic provinces, 737.
distribution, 295–299.
in the United States, 740.
of foreign countries, 741.
persistence, 291.
Petrographic provinces and ore-deposits: practical considerations, 755.
Petroleum: associated with ore-deposits, 344.
oxygenation, 308.
reducing power, 350, 357.
Pharmacist gold-mine, Cripple Creek, Colo., 422, [819].
Philips: deposition of copper from sea-water, 258.
Philipsburg, Mont.: gold-deposits, 814.
Phillips, J. A.: banded structure in ore-deposits, 57.
ore-deposits in vadose region, 171.
Treatise on Ore-Deposits, [5, 12].
Phillips and Lewis: ore-deposits, [282].
pegmatite-dikes at Timbarra, New South Wales, 276.
Phosphate-deposits: formation, 114–115.
Phosphates: in mine-waters, 770.
Phosphorus: distribution in igneous rocks, 749.
in Lake Superior iron-ores, 652.
quantity in igneous rocks, 733.
Piésoclases: definition, 40.
Pilot fault, Leadville, Colo., 48.
Pilot Knob, Mo., iron-ores: occurrence, 87.
Pirsson, L. V.: radial dikes, 394.
Placer-deposits (see also Gold-deposits), 133, 134.

Placers: distribution in western America, 435.
relation to manganiferous gold-deposits, 805.
Plant-remains, Jasper county, Mo., 329.
Plasticity of rock-masses, 44.
Platinum: association with gold in Urals, 289.
distribution in igneous rocks, 753.
in basic rocks, 285.
in igneous rocks, 269.
Plication of rock masses, 44.
Pneumatolysis: definition, 205.
Pneumatolytic origin of ore-deposits, 240.
Pneumatolytic vapors: action, 388.
Pocatello mine, Mineral ridge, Nev., 613.
Pointer mine, Cripple Creek, Colo., 420.
Pontgibaud, France: silver-lead veins, 226.
Porphyry: in Norbotten ore-fields, 675.
percolation by water, 13.
white: Leadville, Colo.: condition and composition, 18.
Leadville, Colo.: source of ore-materials, 18.
Porphyry Dike mine, Rimini, Mont., 221.
Portland mine, Cripple Creek, Colo., 419.
Posepny, Franz: Genesis of Ore-Deposits, v, vii, xiii, 86, 171, 696.
gold in stratified formations, 200.
metals in water of springs, [708].
origin of Sudbury nickel-ores, 485.
Potash: quantity in igneous rocks, 732.
Pre-Cambrian gold-deposits, 434.
production, 435.
Pre-Cambrian series of the Lake Superior region, 634.
Precious metals: greater abundance in vadose region: cause, 206.
Precipitation: circumstances favoring, 30.
of mineral solutions: causes, 37.
ore-materials: conditions favoring, 35.
Pressure: in relation to jointing, 94,
rôle in ore-deposition, 2.
PRICHARD, W. A.: *Observations on Mother-Lode Gold-Deposits, California* [*Trans.*, xxxiv, 454-466], *Notice*, 830.
Prime, F.: on Appalachian iron-ores, 36.
Principles Controlling Ore-Deposition (VAN HISE), xvii.
Promontorio Silver-Mine, Durango, Mexico (LINCOLN), 834.
Prophylitic veins: definition, 438.
gold-production, 441.
Puerticitos mine, Cananea, Mexico, 378, 398.
Pumpelly, R.: copper of Lake Superior region, xxxviii.
genesis of copper-deposits in Lake Superior region, 76.
Purington, C. W.: ore-deposits of San Juan region, Colo., 818.
source of useful metals, 716.
Pyrite: as primary constituent of rocks, 203, 212.
behavior with carbonate solutions, 409.
chemical reactions with chalcocite, [799].
crystallization from magmas, 609.
effect on solubility of galena [766].
in eruptive rocks, 70.
Pyrite: precipitating-agency, 232.
reducing action, 405.
reducing power, 352, 357, 358.
Pyrolusite: association with gold, 793.
Pyroxenes: in rocks of New Zealand: analyses, 167.
Pyrrhotite: analyses, 460.
composition and formula, 458, 475.
Deadwood, S. D., 316.
in diorite, 90.
origin, 460.
relation to chalcopyrite, 513.
reducing power, 355, 358.
Pyrrhotite-deposits: Rossland, B. C., 486.
Pyrrhotites: associated minerals, 478.
classification, 477.
geological relations, 477.

Quartz: crystallization from magmas, 609.
Quartz-porphyry: Cripple Creek district, Colo., 412.
Quartz-veins: origin, 275.
origin as magmatic segregations, 275.
Quartz-Veins of Silver-Peak, Nevada (HASTINGS), xxvi, 621-628.
Quebec: pyrrhotite, 462.
Queensland: gold-quartz veins, 282.
Queen of the West mine, Ten-mile district, Colo.: structural conditions, 62.
Quicksilver, associated with petroleum, 344.
Quicksilver-deposits: alteration, 134.
genesis, 79.
Mirabel mine, Lake county, Cal., 79.

Racine Boy claim: Silver Cliff, Colo., [140].
Radioactive water: analyses, 709.
Rainfall run-off, and evaporation: relation in Colorado, 698.
Rainy River district, Ontario: gold-deposits, 445.
RANSOME, F. L.: *The Geology and Copper-Deposits of Bisbee, Arizona* [*Trans.*, xxxiv, 618-642], *Notice*, 829.
association of gold with manganese, [781].
gold-deposits, Goldfield, Nev., 825.
gold-deposits, Mother Lode district, Cal., 811.
gold-deposits, San Juan region, Colo., 818.
manganese as indication of rich ore, 787.
Ransome, F. L., and Lindgren, W.: gold-deposits, Cripple Creek, Colo., 819.
Raven mine, Cripple Creek, Colo., 420.
RAYMOND, R. W.: *Preface*, v.
Discussion on *The Torsional Theory of Joints*, 101-103.
charcoal between lava flows, 319.
Geological Distribution of Mining Districts in the United States, [65].
gold-deposits, Summit district, Colo., [823].
King's meridional zones of mineral-deposits, [81],
origin of ore-deposits, [242].
Reports on Mines and Mining West of the Rocky Mountains, [764].
READ, T. T.: *The Secondary Enrichment of Copper-Iron Sulphides* [*Trans.*, xxxvii, 297-303], *Notice*, 832.

Real del Monte district, Mexico: comparison with Tonopah, Nev., 601.
Receptacles for ore-deposition: character, 30.
Recrystallization process: San Jose, Tamaulipas, Mexico, 575.
Red Cliff region, Colo.: ore-deposits, 36.
Red Mountain, Ouray county, Colo.: occurrence of ore, 831.
ore-deposits, 31–32.
Red Spruce mine, Cripple Creek, Colo., 429.
Reducing action of volatile hydrocarbons, 346.
Reducing power of minerals, 347, 357.
Reid, J. A.: analyses of vadose waters: Comstock lode, 802.
silver-content of mine-waters, 800.
Repeated movements along fissure-planes, 59.
Replacement-deposits: Rocky mountains, 10.
Replacement iron-deposits: Appalachians, 36.
Replacement-theory: ore-deposits, 8, 9.
Rhodochrosite: reducing power, 358.
Rhyolite: near Silver Cliff, Colo., 139, 143, 157.
Rhyolite-dacite: Tonopah, Nev., 592.
Richthofen, F. von: genesis of Comstock lode, ix, 85.
mineralization of the Comstock lode, 598.
Natural Classification of Eruptive Rocks, [ix].
production of Comstock lode, 803.
proportion of gold to silver in Comstock lode, 802.
Rickard, T. A.: bonanzas in gold-veins, [797].
formation of bonanzas, 761.
mineral veins varying with country-rock, 226.
ore-deposits of Rico, Colo., [330].
origin of ores of Bendigo reefs, Australia, [208].
reduction of ore-bodies by black shale, 331, 332.
solution of gold, 773.
vein-structure, 221.
vertical distribution of ores, [407].
Rico, Colo., veins, 226.
RITTER, E. A.: *The Evergreen Copper-Deposits, Colorado* [*Trans.*, xxxviii, 751–765], *Notice*, 835.
Robertson: analyses of rocks of Missouri, [209].
Rock-flowage: locus and conditions, 711.
relation to earthquakes, 712.
Rock-fracture: causes, 41.
effect on water-channels, 34.
Rock-fractures: character and extent, 39.
classification, 40.
complexity, 92.
Rock-intrusions (see Intrusions).
Rock-masses: plication and fracture, 44.
rigidity and plasticity, 43.
Rocks: changes due to contact metamorphism, 384.
crystalline: classification, 68.
determination of age, 68.
Rocks: eruptive: analyses, 705.
emissions, 236.
geological age, 66.
Leadville, Colo.: mode of eruption, 18.
source of ore-materials, 15.
tests for ore-materials, 16.
source of vein-materials, 20–22.
Tamaulipas, Mexico, 561.
gaseous content, 767.
igneous: average composition, 734.
central Sweden, 657.
origin, 659.
chlorine-content, 767.
crystallization: order in, 261.
derivation from refusion of stratified rocks, 21.
determination of age, 67.
general chemical composition, 730, 734.
geological age, 66.
origin, 67, 259.
Rôle in the Formation of Veins (KEMP), xix.
segregation or differentiation, 259.
superficial: lack of ore-materials, 20.
influence on vein-structure, 217.
New Zealand: examination, 167–168.
permeability to water, 29.
Queensland: examination, 168.
salts in waters of non-calcareous, 764.
secular decay, 112.
sedimentary, at Leadville, Colo.: tests for ore-materials, 16–17.
distribution of metals, 254.
stratified: derivation from igneous rocks, 21.
Victoria; examination, 168.
Rock-segregation: unknown finer laws, 265
Rohn, Oscar: Bullfrog and Kawich districts, Nevada, 600.
Rolker, Charles M.: ore-deposits at Leadville, Colo., 13, 18.
Roscoe and Schorlemmer: analysis of seawater, [195].
Rose, G.: forms of gold from precipitation, 105.
specific gravities of gold, 106.
Rosenbusch, H.: contact-metamorphic phenomena, 524.
Rosita, Colo.: *Mines* (EMMONS), 139–161.
Rossland monzonite, Rossland, B. C., 495.
Rossland, B. C.: pyrrhotite-deposits, 486.
Rotation in faulting, 102
Rothwell, R. P.: charcoal in silver-bearing sandstones, 319.
Silver Reef district, Utah, 326.
Rounding of rock-fragments: origin, 46.
RUMBOLD, W. R.: *The South African Tin-Deposits* [*Trans.*, xxxix, 783–789.], *Notice*, 832–833.
The Tin-Deposits of the Kinta Valley, Federated Malay States [*Trans.*, xxxvii, 879–889], *Notice*, 832.
Rupture: angle of, 104.
by shear, 98.
torsional: character, 99.
Rupture-surfaces, experimentally produced, 97.
Russell, Clarence: compilation of analyses, 763, 765.
Rutile: occurrence in veins of Alaska, 586, 587.

Saline deposits: formation, 115.
Salisbury mine, Silver Peak district, Nevada, 627.
Salt: in sedimentary rocks, 766.
Sandberger, F.: derivation of vein-materials, 22.
genesis of ore-deposits, 14, 86, 204.
Sandstone: chlorine-content, 766.
San Jose district, Tamaulipas, Mexico: geology, 559.
geological map, 560.
ore-deposits, 237.
situation, 559.
San Jose deposits, Tamaulipas, Mexico: map showing location, 558.
San Juan region, Colo.: fissure-faulting, 50.
gold-deposits, 818.
Sankowsky, Nicholas: compilation of analyses, 763, 765.
San Pedro, N. M.: ore-deposits, [238].
Savant lake, Ontario: gold-deposits, 446.
Saxony: Berggiesshübel ore-deposits, 378.
Freiberg: Gottlob vein, 218.
Scandinavian Iron-Ores, *The Geological Relations of* [SJÖGREN), xxvi, 657-695.
Scandinavian lake- and bog-ores: distribution and origin, 694.
Scheerer: amount of water in magmas, 608.
Schmitz, E. J.: copper-ores in the Permian of Texas, 327.
Schneider, E. A.: experimental tests on colloidal sulphides of gold, [xxiv].
Schrader and Brooks: quartz-veins in Nome region, Alaska, 280.
SCHWARZ, T. E.: *Features of the Occurrence of Ore at Red Mountain, Ouray County, Colo.* [*Trans.*, xxxvi, 31-39], *Notice*, 831.
Science of Ore-Deposits: *Bibliography* (IRVING, SMITH, FERGUSON), 837-928.
Scientific method of study, 70.
Scotland: Sutherland gold-fields, 281.
Secondary concentration: ore-deposits, 74.
Sudbury, Ont., ore-deposits, 90.
Secondary enrichment: *Copper-Iron Sulphides* (READ), 832.
criteria for recognition, 791.
gold-deposits, 761.
of metals, 785.
ore-deposits, 326.
sulphide ores, xl.
Secular contraction of earth's crust, 42.
Security-Geyser mine: Silver Cliff, Colo., 142.
Sedimentation: agency in producing water-channels, 33.
Sediments: aggregate thickness, 22.
Segregation of igneous rocks: laws, 261.
Segregation of rock materials: cause, 260.
Selenium: mode of occurrence, 326.
occurrence in Silver Reef, Utah, sandstones, 325.
relations to igneous rocks, 754.
Selwyn, A. R. C.: auriferous rocks of Victoria, 163.
Sénarmont: synthetic experiments, [2].
Sentinel mine, Silver Peak district, Nevada, 626.
Serpentine: metamorphic origin, 75.
Sewell, H.: silver-ore associated with coal, 321.
Shale: oxidation, 536.
Shaler, N. S.: origin of limonites, 124.
Shales: chlorine-content, 766.
Sheeting of country-rock, 46, 47.
Shuler, D. P.: magnetic separation of nickel-ores, 469.
Siderite: reducing power, 358.
Silica: in mine-waters, 770.
quantity in igneous rocks, 732.
Silver: association with gold, 182.
assays, [17], 161.
determination of small amounts in sea-water, 829.
distribution in igneous rocks, 752.
in assays of California rocks, 301.
in mine-waters, 800.
in rocks of New Zealand, 170.
in sea-water, 191.
native: in Lake Superior district, 76.
precipitation by black shales, 331.
removal by solution, 116.
salts: reactions, 115.
tests for: in rocks at Leadville, Colo., 16-17.
Silver City district, Idaho: comparison with Tonopah, Nev., 601.
Silver Cliff, Colo.: country-rock: assays for silver, 161.
investigations of country-rocks, 23.
Mines (EMMONS), xvi, 139-161.
mines in rhyolite: geology, 139.
ore-deposits: genesis, 155.
silver-mines: production, 141.
surface-deposits, 140.
Silver Cliff and Cripple Creek ore-deposits compared, 158.
Silver-deposits: alteration, 131.
association with eruptive rocks, 80.
Colorado: Silver Cliff region, 157.
Bassick mine, 158.
Ben Eaton mine, 157.
Bull-Domingo mine, 158.
Democrat mine, 157.
genesis, 155.
Summit district, [823].
concentration, 80.
New Mexico, Lake Valley: genesis, 835.
Silver-gold and gold-silver ores: vertical relations in deposits, 799.
Silver-gold deposits: associated minerals, 825.
Nevada: Tonopah, 824.
Silver-gold mines (see also Gold-silver mines):
Mizpah, Tonopah, Nev., [825].
Montana-Tonopah, Tonapah, Nev., [825].
Silver-gold ores: Comstock lode, Nev., 800.
Silver-Islet mine, Lake Superior, 231.
gas-flows, 346.
Silver-lead deposits: Colorado: Georgetown and Silver Plume, 816.
in dolomitic limestone, 1.
Silver-lead-gold deposits: Leadville, Colo., 815.
Silver-lead mines, Neihart, Mont., 219, 220.
Silver Ledge, Mercur district, Utah: origin, 290.
Silver-mine: Mexico, Durango (Promontorio), 834.

Silver-mine waters: salts in, 764.
Silver-ore: Leadville, Colo., 800.
Mineral ridge, Nevada: genetic relations, 613.
mode of occurrence, Silver Cliff, Colo., 140.
Neihart, Mont., 800.
Silver Cliff, Colo.: treatment, 141.
Silver-ores of West: origin, 136.
Silver Peak, Nevada: geology and ore-deposits, 622,
gold-deposits, 813.
ore deposits: origin, 628.
Quartz-Veins (HASTINGS), xxvi, 621–628.
Silver Peak quadrangle, Nevada: geology, 603.
mineral veins, 607.
Silver Reef ore-deposits, 36.
Silver-salts: solubilities, 800.
Silver-veins, Butte, Mont., 223.
Silvestri, O.: copper in volcanic fumes, 721.
Similkameen type of ore-deposits, 383.
Sinter: analyses, 149, 629.
Sinters: Geyser mine, Silver Cliff, Colo., 148.
Sjögren, A.: iron-ores of Taberg, Småland, 681.
SJÖGREN, HJALMAR: *The Geological Relations of the Scandinavian Iron-Ores*, xxvi, 657–695.
Skarn: definition, 657.
Skölar: formation, 669.
"Slickenside"-surfaces: fissures, 45.
Slickensiding: in joints, 93.
Smith, Alexander: chemical reactions in solution of gold, [777].
chemistry of manganese, 780.
SMITH, H. D., IRVING, J. D., FERGUSON, H. G.: *Bibliography of the Science of Ore-Deposits*, 837–928.
SMITH, GEORGE: *The Garnet Formations of Chillagoe Copper-Field, North Queensland, Australia* [*Trans.*, xxxiv, 467–478], *Notice*, 830.
Smith, J. Alden: deposition of ores by ascending solutions, 12.
Smyth, R. Brough: gold-fields of Victoria, 171.
Soda: quantity in igneous rocks, 732.
Soda mine, Silver Peak district, Nevada, 627.
Solfataras: source of ores, 84.
Solution chambers: formation, 5.
Solutions: rôle in ore-deposition, 2.
Some Practical Suggestions Concerning the Genesis of Ore-Deposits (BOEHMER), 829–830.
Songbird mine; Silver Cliff, Colo., [140].
Sonstadt, E.: gold in sea-water, 192.
methods of detecting gold in sea-water, 193.
Sonstadt's solution: disadvantages, 166.
Soret's principle of cooling solution, 67.
Soret's principle of molecular flow, 260.
South African Tin-Deposits (RUMBOLD), 832–833.
Southern Klondike district, Nevada, ore-deposits, 618.
Spaltenverwerfungen (fissure-faults): definition, 41.
SPENCER, A. C.: *Geology of the Treadwell Ore-Deposits, Treadwell Island, Alaska* [*Trans.*, xxxv, 473–510], *Notice*, 830.
The Magmatic Origin of Vein-Forming Waters in Southeastern Alaska, xxvi, 582–589.
The Origin of Vein-Filled Openings in Southeastern Alaska [*Trans.*, xxxvi, 581–586], *Notice*, 831.
Treadwell gold-mines, Alaska, [811].
Sperrylite: in diorite, 90.
Sudbury district, Ontario, 463.
Spherulites: Silver Cliff, Colo., 140.
Spring waters: analyses, 706.
Springs: Nevada region: source, 597.
production, 33.
SPURR, J. E.: *A Consideration of Igneous Rocks and their Segregation or Differentiation as Related to the Occurrence of Ores*, xxii, 251–303.
Genetic Relations of the Western Nevada Ores, xxvi, 590–620.
convection currents in magmas, 260.
differentiation in igneous rocks, 261.
gold-deposits, Silver Peak, Nev., [813].
magmatic differentiation, 722.
metallographic provinces, 756.
ore-deposits of Silver Peak quadrangle, 621.
silver-gold deposits, Tonopah, [824].
Spurr and Garrey: ore-deposits of Georgetown, Colo., 816, 817.
Spurr, Garrey, and Ball: silver-lead deposits, Georgetown and Silver Plume, Colo., [816].
Ställberg mines, Sweden: plan, 664.
Standard mine, Bodie, Cal.: vein-system, 833.
Steamboat Springs, Nevada: ore-deposition, 86.
stibnite at, 629.
Stelzner: origin of ore-deposits, [201].
Step-faults, Leadville, Colo., 49.
Sternbeck, R. von: specific gravity of earth, 715.
Stetefeldite, Mineral ridge, Nevada, 614.
STEVENS, E. A.: *Basaltic Zones as Guides to Ore-Deposits in the Cripple Creek District, Colorado*, xxiii, 411–423.
Stevens, Hazard: ascent of Mt. Rainier, [xxxiii].
Stibnite: at Steamboat Springs, Nevada, 629, 631.
reducing power, 354, 358.
Stobie mine, Blezard township, Sudbury district, Ontario, 499.
photomicrographs of ore, 487–488.
Stokes, H. N.: action of pyrite and marcasite, 409.
reaction with pyrite in production of chalcocite, 799.
solution of gold, 771, 772.
Stratification: agency in producing water-channels, 33.
Stretch, R. H.: "compression-veins," 221.
mineral-veins varying with country-rock, 225.
vein-contents and country-rock, 233.
Striations: fissures, 45.
Stringers: definition, 51.
Strong mine, Cripple Creek, Colo., 419.

Strontium: distribution in igneous rocks, 747.
quantity in igneous rocks, 733.
Stutzer, O.: genesis of iron-ores of Norbotten, Sweden, 678.
Styria: iron-deposits: surface-action, 126.
Sublimation theory of ore-deposition, 2, 204.
Substitution theory: ore-deposits, 8.
Subterranean water: limiting depth, 44.
Subterranean waters: Geyser mine, Silver Cliff, Colo., 148.
Sudbury district, Ontario: metamorphism, 514.
Sudbury, Ontario, nickel-region: minerals, 456.
nickel-deposits, 90–91.
geology, 479, 481.
nickel-ores: genesis, 477.
Ore-Deposits (DICKSON), xxiv–xxv, 455–516.
Sudbury mattes: composition, 465.
Sudbury ores: assays, 464.
origin: microscopical evidence, 497.
Suess, Eduard: formation of mineral veins by gaseous emanations, 389.
gold resources of the world, 425.
hot springs of Carlsbad region, 369.
ore-deposits derived from igneous emanations, [368].
origin of ore-deposits, 391.
Sullivan, E. C.: chemical relations of iron and manganese in rocks, 795.
experimentation on copper-iron sulphides, 832.
Sulphates: effect on solution of gold, 772, 775.
in mine-waters, 766.
solution and precipitation of manganese by, 795.
Sulphide secondary enrichment: ore-deposits, xvii.
Sulphides: alteration, 2.
deep: formation, 183.
in rocks, 163.
secondary: definition, 183.
Sulphur: distribution in igneous rocks, 750.
quantity in igneous rocks, 734.
reducing power, 307, 351, 357.
Sulphuretted hydrogen: reducing power, 352, 357.
Summary of Lake Superior Geology with Special Reference to Recent Studies of the Iron-Bearing Series (LEITH), xxvi, 633–656.
Summit district, Colo.: gold-deposits, 822.
Summit gold-mine, Cripple Creek, Colo., [819].
Sunrise gold-mine, Macetown, N. Z.: assays, 184.
Sunrise mine: Silver Cliff, Colo., [140].
Superficial Alteration of Ore-Deposits (PENROSE), xv.
Surface-alteration: varying depths, 121.
Surface-waters: definition, 6.
varying action on ore-deposits, 116.
Sutro, A.: genesis of Comstock lode, x.
Svartvik mines, Sweden: section, 665.
Sweden: map of ore-province, 658.
titaniferous iron-ore: concentration in magmas, 72.
Swedish iron-deposits: lake region: concentration, 127.
Syenite: in Norbotten ore-fields, 675.
treatment for isolation of hornblende, 165.
Synclases: definition, 40.

Taberg, Sweden, iron-district: map, 683.
Taberg mines, Sweden: origin of iron-ores, 668.
Telluride type of ore-deposits, 372.
Tellurium: relations to igneous rocks, 754.
reducing power, 358.
Temperature: increase with depth, 246.
of descending column of water, 245.
of fluid magmas, 724.
rate of increase in earth's crust, 713.
Ten-Mile district, Colo.: investigations of country-rocks, 23.
ore-deposits, 36.
Tephrite: Cripple Creek district, Colo.: 412.
Tertiary gold-deposits, 438–441.
Tertiary volcanic rocks, Tonopah, Nev., 591.
Tetrahedrite: reducing power, 358.
Thames district, N. Z.: vadose and deep vein-gold: assays, 185.
Thermal springs: ore-deposition, 406.
Thompson mine, Cripple Creek, Colo., 420.
Thomsen, J.: chemical properties of gold, 107.
forms of gold from precipitation, 105.
Thorium: distribution in igneous rocks, 749.
Thunder Bay, Canada, silver-veins, 231.
Tibbey, B.: hydrocarbon-gas in Illinois mine, Montana, 346.
Tiberg, H. V., iron-ores of Sweden, 665, 669.
Time in geologic operations, 700.
Tin: distribution in igneous rocks, 753.
in siliceous rocks, 285.
Tin chloride test for gold, 194.
Tin-deposits: Alaska, Cape Prince of Wales: geology and mining, 833.
alteration, 133–134.
Kinta Valley, Federated Malay States (RUMBOLD), 832.
South African, 832.
Tin-veins: occurrence, 287.
Tinguaite: San Jose, Tamaulipas, Mexico, 565.
Tipperary Premier gold-mine, Macetown, N. Z.: assays, 184.
Titaniferous iron-ore: concentration in magmas, 72.
Norway, 72.
Sweden, 72.
Titanium: distribution in igneous rocks, 749.
Titanium dioxide: quantity in igneous rocks, 733.
Tomboy gold-mine, Silverton, Colo., [818].
Tonopah, Nevada: geology, 591.
mineral veins, 593.
silver-gold deposits, 824.
Topography: effect on depth of alteration, 120.

Tornado mine, Cripple Creek, Colo., 420.
Törnebohm: iron-ores of Taberg, Småland, 681.
Torsion: effects, 51.
experiments on glass plates, 95
of rock-masses, 45.
Torsion-fractures: character, 95.
Torsional rupture: character, 99.
Torsional Theory of Joints (BECKER), xiii, 92–104.
Tourmaline: occurrence in ores, 586.
Toyabe range, Nevada: ore-deposits, 617.
Travers, M. W.: origin of gas in mineral substances, 389.
Treadwell gold-silver mine, Douglas Island, Alaska, 811,
Treadwell ore-deposits: Alaska, Douglas Island, 830.
Tremolite: San Jose, Tamaulipas, Mexico, 569.
Triumph mine, Cripple Creek, Colo., 419.
Tungsten in siliceous rocks, 285.
Tuollavaara iron-ore deposits: Sweden, 673.
Turner, A. T.: Sudbury mattes, 465.
Turner, H. W.: field-work in Silver Peak region, Nevada, 604.
quartz-veins at Silver Peak, Nevada, 276.

Ulrich, G. H. F.: auriferous rocks of Victoria, 283.
rocks of Otago peninsula, N. Z., 166.
Uncle Sam mine, Tintic district, Utah, 339, 340, 343.
Underground water: agency in formation of Lake Superior iron-ores, 644.
circulation: factors, 237.
derivation, 236.
direction of flow, 14.
Union Belle mine, Cripple Creek, Colo., 420.
United States Geological Survey: founding, [xxxiii].
Urals: relations of gold and platinum, 289.
Uranium: distribution in igneous rocks, 749,
Utah, Dry Cañon, Mono silver-mine, 332.
Mercur district: gold-production, 437.
vein system, 290.
Silver Reef: geologic structure, 325.
ore-deposits, 322.
silver-ore in sandstone, 320.
Tintic district ore-deposits, 335–340, 362.

Vadose country-rock at different distances from auriferous lodes: examination, 183.
Vadose region: greater richness of gold-deposits, 171.
Vadose waters, xiv.
Valcalde mines, Silver Peak district, Nevada, 626.
Vanadium: association with coal, 321.
distribution in igneous rocks, 750.
in basic rocks, 285.
Vanderbilt mine, Mineral Ridge, Nev., 613.
Vanderbilt mine: Silver Cliff, Colo., [140].
Van Diest, E. C. and P. H.: Rito Seco gold-deposits, Costilla county, Colo., 447.
Van Hise, C. R.: classification of Algonkian rocks, 69.
critical temperature of water, 713.
development of rocks of Lake Superior region, 648.
fissures at Cripple Creek, Colo., 221.
formation of secondary copper sulphides, 533.
genesis of ore-deposits, [252].
iron-ores: origin, 70.
magnetite in magmas, 72.
meteoric waters, 240.
origin of iron-ores of Michigan and Wisconsin, 124.
origin of pegmatite, 275.
principles of ore-deposition, xvii, [235], 696, [761].
zone of flowage, 699, 711.
zone of fracture, 711.
Veins: comb-structure, 10.
dependence on rock-structure, 217.
derivation of mineral contents, 14.
frequency, 248.
productive: explanation, 718.
relation to trap rocks, 20.
view of older geologists as to their nature, 84.
Vein-enrichment: *by Ascending Hot Waters* (WEED), xxiii, 403–410.
Vein-fissure: Ontario mine, Utah, 61.
Vein-material: source, 53, 161.
Vein-materials: derivation from adjoining rocks, 22–24.
derivation from eruptive rocks, 19–22.
Leadville, Colo.: source, 16.
Vein-structure: influence of rocks, 217.
Vein-system: Cornwall, England, [52].
Erzgebirge, Freiberg, Saxony, 52.
Standard Mine, Bodie, Cal. (BROWN), 833.
Vein-systems: age and relations, 290.
Vein-walls: structural features, 54.
Butte, Mont., 55.
Gunnison region, Colo., 55.
Vermilion Creek Basin, Wyoming: diamond swindle, [xxxiii].
Vermilion iron range: vertical section, 640.
Vermilion River, Ontario: gold-deposits, 445.
Vesuvianite: San Jose, Tamaulipas, Mexico, 572.
Victor mine, Cripple Creek, Colo., 423.
Victoria: gold-quartz veins, 282.
Victoria mine, Denison Township, Sudbury district, Ontario, 505.
photomicrographs of ore, 490.
Vindicator mine, Cripple Creek, Colo., 422.
Virginia: Virgilina: copper-veins, 220.
Vogelsang, H.: petrographic provinces, 737.
Vogesite: San Jose, Tamaulipas, Mexico, 567.
Vogt, J. H. L.: chromite in Norway, [268].
contact-metamorphic phenomena, 525.
distribution of rare elements, 745.
genesis of ore-deposits, [253], 403.
genesis of titaniferous iron-deposits of Sweden, xiii.
geology of ore-deposits, [222].
iron-ores of Christiania region, 692.
nickel in basic rocks, 295.
origin of nickel-ores, 484.

Vogt, J. H. L.: rare chemical elements, 737.
secondary enrichment, xxxix.
source of iron, 205.
titaniferous iron-ores of Norway, [111].
Volcanic eruptions: sequence in connection with sequence of metalliferous veins, 288.
Volcanic gas: analysis, 388.
Vom Rath: Elba iron-ores, 8.
Von Foullon: Sudbury nickel-ores, 482.
Vrang, C. H.: iron-ores of Sweden, 665.
Vulcanism: expiring: cause of ore bodies 721.
relation to ore-deposits, 239.
vein forming by, 704.

WAGONER, LUTHER: *The Detection and Estimation of Small Quantities of Gold and Silver* [*Trans.* xxxi, 798–810], *Notice*, 829.
assays of California rocks, 301.
petroleum associated with quicksilver, 344.
Walferdin: temperatures in earth's crust, 714.
Walhalla, Victoria, gold-bearing rocks: analyses, 186.
gold in country-rock: curves showing, 192, 193.
vadose country-rock: analyses, 186.
Walker, T. L.: sperrylite associated with chalcopyrite, 463.
Sudbury nickel-ores, 484.
Wallace mine, near Whitefish River, Ontario, 508.
Wall-pyrite: origin and content, 207, 214.
Wall-rocks: permeability to solutions, 207.
Walls (see Vein-walls).
WASHINGTON, H. S.: *The Distribution of the Elements in Igneous Rocks*, xxviii, 726–758.
analysis of analcite-tinguaite, 566.
analysis of nephelite-syenite, 562.
Washoe, Nev.: investigations of country-rocks, 23.
Water (see also Mine-waters):
agency in producing breccia, 47.
amount in magmas, 608.
analysis, 630.
compression, 244.
descending: temperature, 245.
films: action in joints, 93.
Geyser mine, Silver Cliff, Colo: analyses, 150.
in igneous rocks, 262.
ingredients, 113.
movement in porphyry, 13.
oxidizing agents lost in descending, 6.
quantity in crystalline rocks, 733.
rôle in magmas, 731.
stability, 314.
underground: direction of flow, 14.
limiting depth, 44.
velocity moving through a channel, 450.
Water-channels: in eruptive rocks, 33.
locus at Leadville, Colo., 13.
natural: causes, 33.
Water-courses: Geyser mine, Silver Cliff, Colo., 147.
"Water-level": locus, 6.
Waters, ascending, 85.
circulating in earth's crust: channels for, 30.
deep-seated, xiv.
in mines: analyses, 765, [779].
salts in, 764.
silver- and gold-content, [800].
natural, chlorine-content, 767.
vadose, xiv.
Water-table: definition and characterization, 788.
relation to chemical activity, 788.
seasonal variation, 788.
WATSON, T. L.: *Geology of the Virginia Barite-Deposits* [*Trans.*, xxxviii, 710–733], *Notice*, 834.
Lead- and Zinc-Deposits of the Virginia-Tennessee Region [*Trans.*, xxxvi, 681–737], *Notice*, 831–832.
The Occurrence of Nickel in Virginia [*Trans.*, xxxviii, 683–697], *Notice*, 834.
Yellow Ocher Deposits of Cartersville District, Bartow County, Ga. [*Trans.*, xxxiv, 643–666], *Notice*, 830.
Wells: temperatures in, 714.
Wells, R. C.: reactions in dissolving gold, 777.
reactions of manganese compounds, 785.
services rendered by, 764.
WEED, W. H.: *Influence of Country-Rock on Mineral Veins*, xxi, 216–234.
Ore-Deposition and Vein-Enrichment by Ascending Hot Waters, xxiii, 403–410.
Ore-Deposits Near Igneous Contacts, xxiii, 364–402.
Enrichment of Gold and Silver Veins, xviii.
form of contact-deposits, 528.
mineral vein-formation at Boulder Hot Springs, Montana, [247].
minerals of secondary origin, [792].
secondary enrichment of gold and silver veins, [761], [815].
Weed and Barrell: Elkhorn district, Mont., ore-deposits, [239].
Weidman, S.: origin of Baraboo iron-ores, 651, 652.
White, David: plant-remains in Missouri, [329].
White Knob Copper Deposits, Mackay, Idaho (KEMP and GUNTHER), 833.
Whitney, J. D.: locus of metalliferous veins, 280.
ore-genesis, [viii].
The Metallic Wealth of the United States, [110].
Williams, G. H.: origin of pegmatite, 275.
Wilson, A. D.: ascent of Mt. Rainier, [xxxiii].
WINCHELL, A. N.: *Discussion on A Consideration of Igneous Rocks and their Segregation or Differentiation as Related to the Occurrence of Ores*, 303–304.
Winchell, H. V.: genesis of chalcocite at Butte, [761].
genesis of copper-ores, 402.
origin of iron-deposits of Mesabi range, Minn., 125.
pyrite as a precipitant, 232.
synthesis of chalcocite, 533.
Thunder Bay silver-veins, 231.

WINSLOW, ARTHUR: *Discussion on Geological Distribution of Useful Metals in the United States*, 86–89.
Discussion on The Genesis of Certain Auriferous Lodes, 208, 211.
lead- and zinc-deposits of Missouri, [209].
Wisconsin lead-ores, 334.
Wolf, T.: volcanic gases, 723.
Wollastonite: contorted zones, Durango, Mexico, 578.
San Jose, Tamaulipas, Mexico, 570.
Wood lying under sea-water: examination for gold, 197.
Worthington mine, Drury township, Sudbury district, Ontario, 505.
photographs of sections of ore, 493.
Wurtz, Henry: solubility of gold in ferric salts, 173.

Yankee Girl mine, San Juan region, Colo., example of chimney-deposits, 58, 59.
occurrence of ore, 831.
Yellow Ocher Deposits of Cartersville District, Bartow County, Ga. (WATSON). 830.
Yttrium: distribution in igneous rocks, 749.
Yukon: gold-quartz veins: formation, 272.
Yung and McCaffery: ore-deposits of San Pedro district [577].

Zenobia mine, Cripple Creek, Colo., 422.
Zinc: distribution in igneous rocks, 753.
Zinc-blende: effect of pyrite on solubility, [766].
in Geyser mine, Silver Cliff, Colo., 146.
Zinc-deposits: alteration, 131–132.
Zinc: distribution in igneous rocks, 753.
genesis, 77–79.
source of material, 77.
Virginia-Tennessee region, 831.
Zircon: crystallization from magmas, 609.
Zirconium: distribution in igneous rocks, 749.
quantity in igneous rocks, 733.
Zirkel, F.: contact-metamorphic phenomena, 525.
Zone of cementation, 241.
Zone of flowage: effect on open channels, 699.
Zones in ore-deposits, 789.